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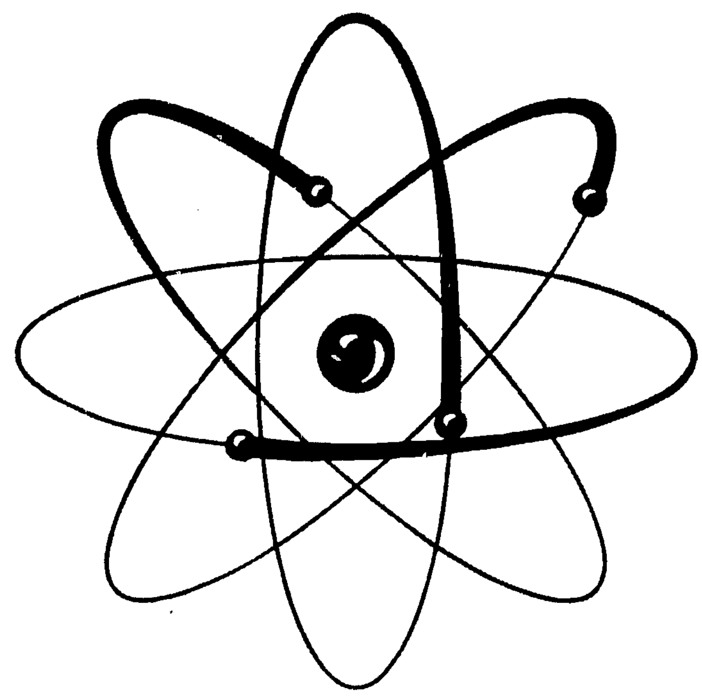
This text was developed for use by students in an 80-hour course for industrial radiographers. Chapter headings are: (1) The Structure of Matter, (2) Radiation and Radiation Machines, (3) Nuclear Reactions and Radioisotopes, (4) Interaction of Radiation with Matter, (5) Radiation Detection and Measurement, (6) The Nature and Consequences of Radiation Exposure, (7) The Effect of Radiation on the Organs and Tissues of the Body, (8) Introduction to Radiography, (9) Elements of Industrial Radiography, (10) Radiographic Film, (11) Radiography Techniques, (12) Interpretation of Radiographs, and (13) Government Licensing, Health, and Transportation Regulations for Isotope Radiography. A study guide (VT 006 294) and instructor's guide (VT 006 292) are also available; each has the same topical arrangement as this text. (EM)



INDUSTRIAL RADIOGRAPHY

Manual

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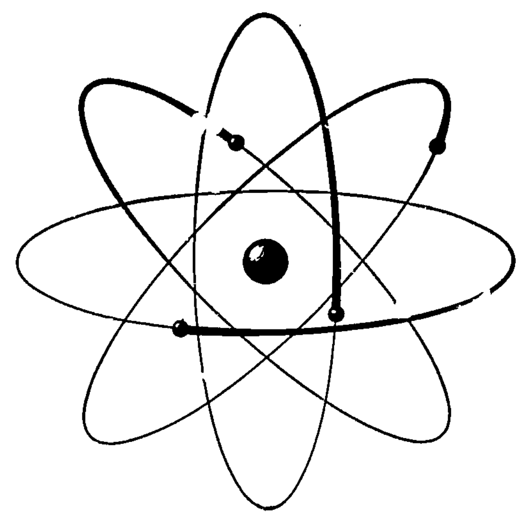

INDUSTRIAL RADIOGRAPHY Manual

Developed jointly by the Division of Vocational and Technical Education of the U.S. Office of Education and the Division of Nuclear Education and Training, U.S. Atomic Energy Commission.

Developed and first published pursuant to a contract with the U.S. Atomic Energy Commission by Harry D. Richardson.

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Foreword

Nondestructive testing has become an indispensable tool of industrial production. It resulted from a rapid flow of technological advances which are an outcome of the large investment in scientific research and development. Management in modern industry can utilize one aspect of nondestructive testing, known as industrial radiography, to reduce production costs and assure product quality in a competitive market. Specifically, design engineers, metallurgists, materials engineers, quality control engineers, and maintenance supervisors can apply the techniques of testing with X-rays and radioactive isotopes to insure product reliability; prevent accidents and save human life; decrease losses of production time; eliminate wastage of materials; decrease maintenance time and costs; and maintain high industrial productivity while achieving product integrity and serviceability.

A vital factor in the growth of industrial radiography is the technical personnel involved. They are trained to understand the comparative capabilities, advantages, and limitations of X-rays and radioactive isotopes, and can safely and efficiently make specific application of these energy sources to all types of industrial work.

This resource manual has been developed to assist in the training of industrial radiographers in an 80-hour program. Trainees attending this program are expected to have a formal high school education. The training program, therefore, is most elementary, yet provides the basic knowledge and skills required. The trainee will not become a proficient radiographer in this introductory program, hence, emphasis should be placed upon understanding the basic principles. With a proper understanding of the principles he can improve his abilities through experience and by additional study of the materials contained in the bibliography.

In addition to this trainee manual, the material prepared and coordinated for this course includes*:

Industrial Radiography—Student Guide and Laboratory Exercises
Industrial Radiography—Instructor's Guide

The need for this course was identified by officials in the U.S. Atomic Energy Commission. The Commission's first concern was to eliminate overexposures to workers engaged in radiography. A second interest was to increase the trained manpower in this expanding field. Content and format for the course were identified by a committee of industry repre-

* Student Guide and Laboratory Exercises, *Industrial Radiography*, OE-84035, available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, price 55 cents.

Instructor's Guide, *Industrial Radiography*, OE-84034, available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, price 40 cents.

sentatives working with representatives of the U.S. Atomic Energy Commission and the U.S. Office of Education, Division of Vocational and Technical Education.

The writing of the manual was performed by Harry D. Richardson, Louisiana State University, under contractual arrangements with the Division of Nuclear Education and Training, U.S. Atomic Energy Commission.

GRANT VENN
Associate Commissioner for Adult, Vocational, and Library Programs

RUSSELL S. POOR
Director, Division of Nuclear Education and Training

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Radiation Physics

Most persons entering training to become radiography technicians will have very little information and experience related to ionizing radiations, and their properties and interactions with matter. The reason is that these topics are not taught in many high school programs. Much publicity has been given to A-bombs and H-bombs, their destructive abilities, and their hazards to the human body. Relatively little information has been published on the useful applications of radiation for the technician.

The first five chapters of this study discuss elementary concepts that are necessary for understanding the radiography process and associated safety practices. Each trainee should make a concerted effort to gain a complete working knowledge of these topics.

Chapter 1

The Structure of Matter

1–1 Early Atomic Concepts

Speculations about matter extend back to early Greek times. Thus we find that Democritus, a Greek philosopher who lived about 460 B.C., considered matter to be made up of very small invisible particles. These he called *atoms*, from the Greek work *atomos* which means something that cannot be cut.

Other Greeks did not accept this idea and believed that all substances were made of earth, water, fire, and air. Aristotle considered matter to be composed of mixtures of the four qualities hot, cold, wet, and dry. Thus, dryness and hotness made fire, dryness and coldness made earth, and wetness and coldness made water. Such theories as these persisted until the seventeenth century when scientific progress really began.

At about this time Cassendi of France put forth a theory that the tiny invisible balls of matter had hooks by which they connected together to form a substance. Newton believed that solids, liquids, gases, and light were composed of atoms or small particles that could not be further subdivided.

Lavoisier in 1774 proved that air was composed of two substances—oxygen and nitrogen. He went on to discover and identify twenty of the elements. Later Priestly and Cavendish showed that water was composed of two elements that were normally gases—hydrogen and oxygen.

Then it was discovered that when certain elements combined they always did so in a fixed proportion by weight. John Dalton guessed this meant that elements must be made up of particles that cannot be divided. He also developed some basic ideas about atomic weight using hydrogen as the standard. At about the time of Dalton it was discovered that water could be broken down by connecting two wires to a battery and placing their ends into the water. Oxygen gas bubbled from one wire and hydrogen from the other.

Mendeleev in 1869 developed the periodic table of elements. He was able to place the then known elements in order starting with hydrogen, the one with the smallest weight. Certain properties of elements were repeated and they could be placed in groups. Since not all the elements were known, gaps appeared in Mendeleev's table and he predicted that more elements would be discovered to fill the gaps. He even predicted the properties of these elements. Many of his predictions were found to be correct.

1–2 Later Atomic Discoveries

The Greeks found that if a piece of amber was rubbed with animal fur it acquired the ability to attract lightweight particles of matter. These effects came to be called electricity because the Greek word for amber is "elecktron." Benjamin Franklin's famous kite experiments with electricity are well known. In 1796, Volta produced electricity chemically by using two different pieces of metal between which he placed a piece of wet paper.

Geissler, about the middle of the nineteenth century, showed that electricity could flow through space. He sealed a wire in each end of a glass tube and exhausted the air from the tube. When the wires were connected to an electrical source, there was a discharge through the vacuum in the tube. It was found that rays of some kind came from the negative wire in the tube. They were first called cathode rays, from the Greek word "kathodos" which means negative.

In 1895, Roentgen showed that rays unknown to him at that time, caused certain chemicals to become fluorescent and that they could penetrate solid substances. These were called X-rays. Antoine Henri Becquerel, at about this time, discovered rays coming from uranium salts which blackened photographic plates in their package. Then the Curies isolated from several tons of pitchblende ore, a small bit of material which they called radium. The ability to produce rays which affected photographic film was called "radioactivity."

Rutherford, in England, found that uranium emitted two types of rays or radiation which he called alpha and beta radiation. He laid the foundation for the modern concept of the atom —that it is not a solid particle but mostly empty space with a small solid core or nucleus.

In 1900, Villard, a French scientist, found a third type of radiation which came from some radioactive elements which he called gamma rays. These were found to be somewhat similar to the X-rays discovered by Roentgen.

Albert Einstein, in 1905, proposed his famous theory of relativity, which was the real beginning of modern physics. Many old concepts of classical physics were changed, and a new approach to understanding energy, matter and time was made. Part of his theory, the famous $E = mc^2$ equation, related mass and energy in a new way and foretold the possibility of securing large amounts of energy from a small amount of matter.

In 1913, Niels Bohr proposed a new theory about the forces which hold the atom together. This resulted in a better understanding of the structure of the atom. By 1932, many of the particles making up the atom had been found. Thompson had identified the electron, and Rutherford the proton. Chadwick explained a new kind of radiation by proposing the neutron as a new particle. Thus, the three important building blocks of nature were known.

Discovery followed discovery in rapid succession. New particles were found. Nuclear science was soon to make a great impact on the world with the explosion of an atomic bomb. Einstein wrote his famous letter to President Roosevelt and a crash program of nuclear research began. In 1942, a nuclear chain reaction was produced at the University of Chicago. In 1945, the first atomic bomb was detonated at Alamogordo, New Mexico. A few weeks later atomic bombs destroyed the Japanese cities of Hiroshima and Nagasaki.

In 1946, the Atomic Energy Commission was set up to control atomic energy in this country. Since then scientists have delved deeper into the mysteries of the atom and have developed new weapons of war and new peaceful uses of this source of energy. Radiography, the use of penetrating radiation to make "photographs" of solid materials, has become an important commercial process.

1–3 Particles of Matter

How do we know that a substance is made up of numerous tiny particles? Some simple examples lead us to the reasonableness of this concept of matter. Table salt dissolves when put into water and disappears. So do many substances when placed in water. Where does the salt go? There must be holes in the water for the particles of salt to go. A colored dye placed in a glass of water soon spreads throughout the water. The particles of dye must spread out and fill in spaces between the particles of water.

It is known that a quart of water mixed with a quart of alcohol is less than two quarts of mixture. The particles of one liquid occupy spaces between particles of the other liquid. If two very smooth edges of a bar of gold and a bar of silver are placed together and left, it will be found that some particles of each have mixed with the other bar.

This suggests that a smooth continuous surface of matter is deceiving. Really there are almost countless holes or spaces in all matter. This can be explained by thinking of matter as being composed of tiny small particles or atoms with spaces between the atoms.

1–4 Atoms and Elements

Substances such as hydrogen, oxygen, carbon, gold, silver, iron, and many others are called "elements." Other substances such as wood, rock, rubber, salt, and hundreds of thousands more are combinations of the comparatively few elements. These combinations are called "compounds."

It took many years of work for scientists to find and isolate the elements. Many were known in ancient times, such as silver, gold, and carbon. However, the people did know the elements were different from other substances such as salt or water. Some of the more familiar elements with their chemical symbols are:

Aluminum	Al	Copper	Cu	Nitrogen	N
Calcium	Ca	Gold	Au	Oxygen	O
Carbon	C	Hydrogen	H	Silicon	Si
Chlorine	Cl	Iron	Fe	Silver	Ag
Cobalt	Co	Lead	Pb	Sulfur	S

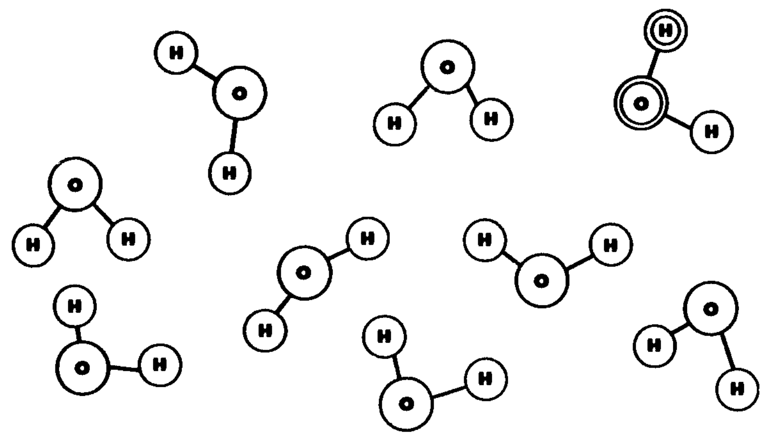
The smallest particles of elements are atoms. For example, consider carbon atoms. Efforts can be made to chemically change atoms by mixing them with acids, alkalis, or other substances. Efforts can be made to physically change atoms by freezing or putting them under great pressure. Even if carbon atoms are heated or burned to form a gas, the carbon atoms can be converted back to their original form. Atoms enter into many combinations with atoms of other elements to form many materials, but other reactions can always reclaim the atoms back from these materials. Therefore, it seems that carbon is an elementary material.

By 1940, nearly 92 of these elementary substances had been found. Seven more were manmade as a result of the development of the atomic bomb. The almost infinite variety of materials in the world is made up of combinations of these elements.

1–5 Molecules and Compounds

Generally, materials which are *not* elements are called compounds (consisting of two or more elements). The smallest is called a molecule. A molecule may be broken down into the atoms that compose it. Water may be broken down into hydrogen and oxygen. Table salt may be broken down into sodium and chlorine.

Atoms making up a molecule of a substance always combine in the same ratio by weight. Thus, if a spark is shot through a tank of hydrogen and oxygen, water will form. For every ounce of hydrogen, eight ounces of oxygen will be used to form water. Each water molecule is composed of one oxygen atom and two hydrogen atoms.



Every water molecule is made up of two atoms of hydrogen joined to one atom of oxygen.

FIGURE 1.1.—Molecules of Water; H_2O.

Until recently, these concepts of atoms and molecules were mainly theories. No one had seen an atom or molecule. However, the electron microscope provides fairly clear pictures of some of the largest molecules such as the proteins. These contain thousands of atoms per molecule. It is noteworthy that the first direct photographs of molecules, looked in size and shape just as scientists had predicted they would.

1–6 Fundamental Particles

Even before the twentieth century, chemists knew that the concept of the atom as a homogeneous tiny ball or particle was wrong. Atoms join together to form molecules. Balls do not fasten together in combinations. Thus, oxygen can hold two hydrogen atoms, as in H_2O or water. Carbon can hold two oxygen atoms, as in carbon dioxide, CO_2. The bonds are often spoken of as valences. Later it will be seen how the chemical union of atoms comes about.

Over a period of years, scientists have discovered that atoms themselves are composed of tiny particles. The fundamental particles which are of primary concern in atomic theory are:

(1) Proton—a particle carrying a unit positive electrical charge. Its mass is approximately one atomic mass unit.*

(2) Neutron—an electrically neutral particle having approximately the same mass as the proton.

(3) Electron—a particle carrying a unit negative electrical charge. Its mass is 1/1840 AMU.

(4) Positron—a particle having the same mass as the electron but with a unit positive electrical charge.

1–7 The Atom as a Solar System

Early in this century, Bohr and Rutherford developed theories that led to the nuclear concept of the atom. The atom came to be viewed as having a small, relatively heavy nucleus. About this nucleus, electrons revolve in path or orbit. The space in the atom outside the nucleus is very large as compared to the size of the nucleus or the electrons going around the nucleus.

The hydrogen atom has a single electron revolving about a nucleus. The hydrogen atom is very small. Its diameter is about 1/200,000,000 of an inch. If the nucleus were enlarged to the

*An atomic mass unit (AMU) is an arbitrarily selected unit of mass which is 1/16 the mass of an oxygen atom.

size of a baseball, the single electron would be nearly half a mile away. Thus, the volume occupied by an atom is almost empty space.

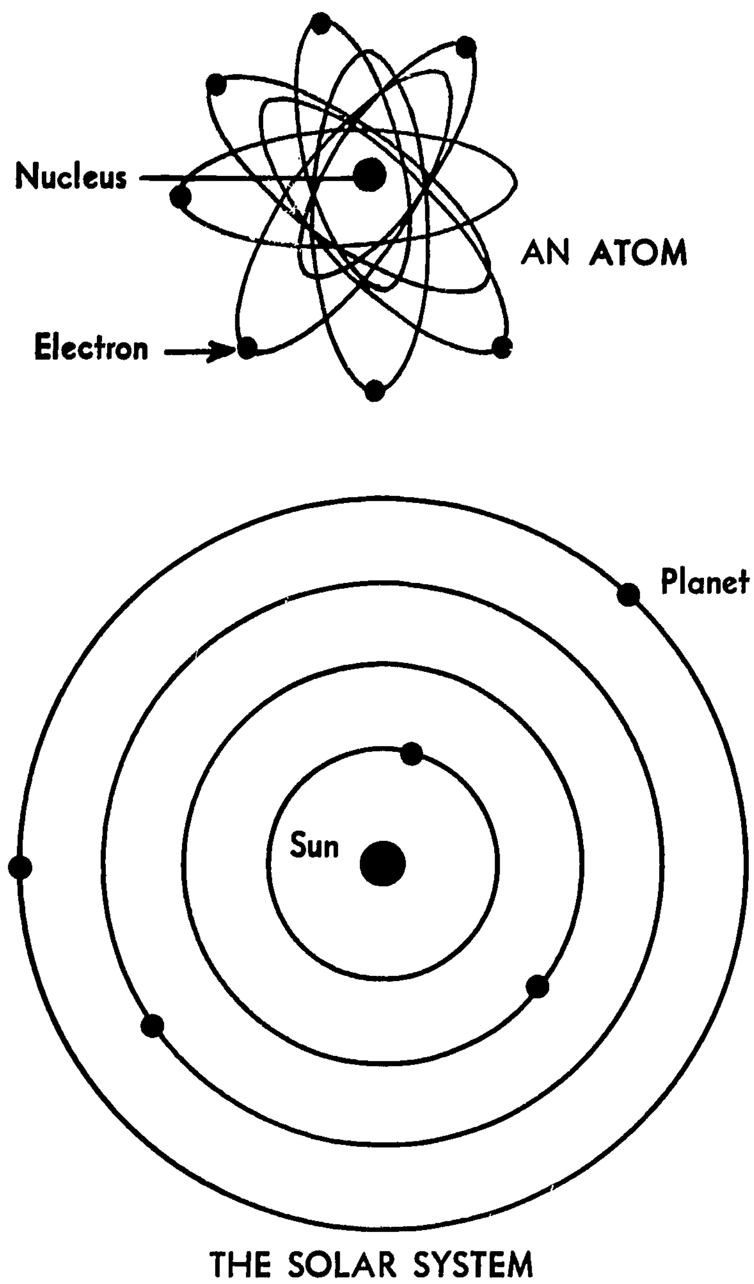


FIGURE 1.2.—The Atom and the Solar System.

The hydrogen atom is the simplest of all atoms and has the assigned atomic number 1.* Other elements have atoms with more protons in the nucleus and more electrons in orbit about the nucleus. The electrons seem to revolve in shells about the atoms. For example, the element potassium has 19 electrons arranged in shells consisting of 2, 8, 8, and 1 electrons. These shells have been designated "K," "L," "M," "N," and so on. Chlorine has 17 electrons, arranged in shells consisting of 2, 8, and 7 electrons. The chlorine atom may seize the single electron on a potassium atom, and the two atoms are said to be united in a chemical reaction.

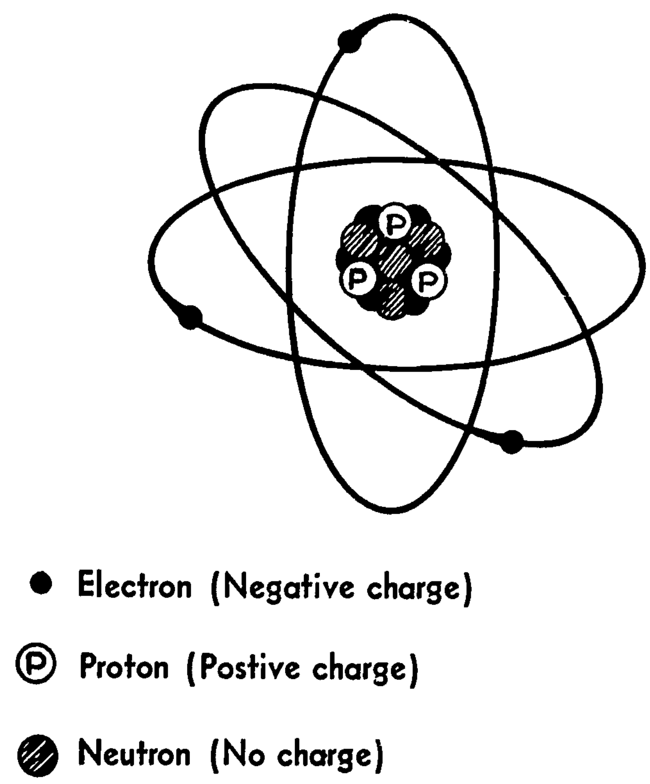


FIGURE 1.3.—Particles in an Atom.

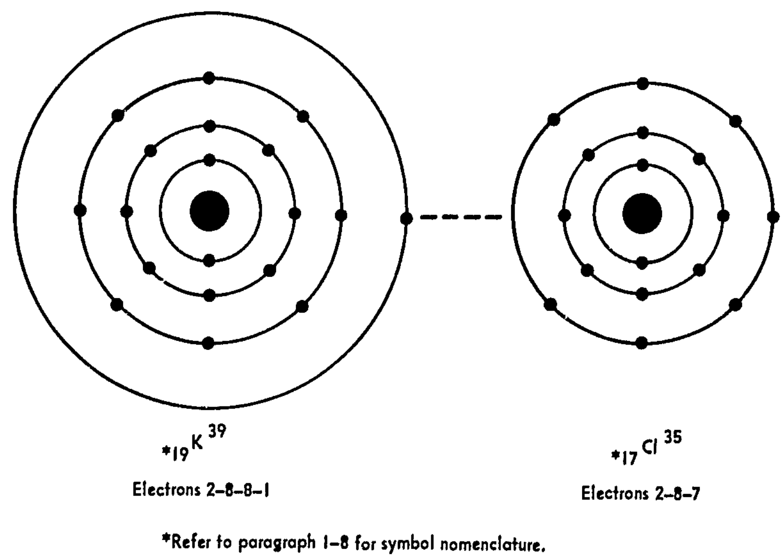


FIGURE 1.4.—Potassium and Chlorine Atoms.

Bohr's basic ideas about atomic structure have been kept in about the same form in present-day theory. His ideas led to the explanation of many experimental results. More modern concepts hold, however, that exact descriptions of the motion or paths of electrons in the shells of atoms cannot be given. It is convenient to think of the shells as clouds of varying densities, one inside the other with the nucleus inside all the cloud-shells. A cross section cut of the

*The atomic number denotes the number of protons in the nucleus, the number of positive charges in the nucleus, and the number of orbiting electrons.

atom would reveal that each cloud-shell varies in density with the probability of finding the electrons in the shell being highest where the cloud-shell was most dense (see Figure 1.5) These shells are sometimes referred to as electron clouds. Such a model or image does not give a precise orbit or path to electrons in a shell. Instead the most dense part of each shell does correspond in radius to the paths described in earlier static models of the atom.

For convenience, pictures showing plane orbits of electrons about the nucleus of the atom may still be used. The path is not so important in some respects as are the energy levels of the electrons. Straight horizontal lines may be used to denote energy levels of electrons in the shells. This is a useful way of visualizing energy relationships of electrons.

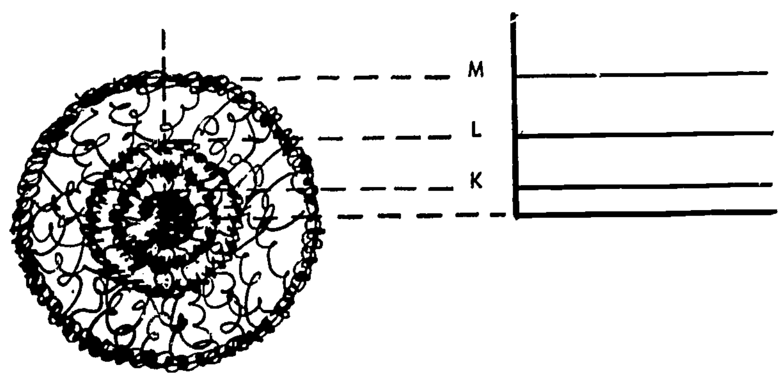


FIGURE 1.5.—Electron Cloud Density and Energy Levels.

1–8 Atomic Number and Weight

While the electron arrangement in the shells outside the nucleus of an atom is of interest to the chemist, the nucleus itself is of interest to the physicist. The nuclei of atoms are made up of protons and also neutrons (with the single exception of the simplest hydrogen atom). The charge on the nucleus of an atom is determined by the number of protons in the nucleus. The 92 elements found in nature have been numbered from 1 to 92. Number 1 is hydrogen and number 92 is uranium.

Symbols for the elements are commonly written with subscripts and superscripts. Examples:

hydrogen	$_1H^1$	oxygen	$_8O^{16}$
helium	$_2He^4$	uranium	$_{92}U^{238}$

The subscript is called the atomic number and denotes the nuclear charge or number of protons in the nucleus. The superscript refers to the sum of the neutrons and protons in the nucleus. Also, this superscript is approximately the atomic weight.

The weight of one carbon atom has been arbitrarily set as 12 units of mass. On this basis, the atomic weights of other elements have been determined. Examples:

hydrogen	1.008	cobalt	58.9
helium	4.003	lead	207.1
nitrogen	14.0	uranium	238

Note that these are very nearly whole numbers.

Dalton's atomic theory came early in the nineteenth century. It motivated a search for elements which by the middle of the century resulted in the discovery of some 75 elements. Study of these showed that they differed in atomic weight and that, furthermore, they could be placed in serial order. Also noted was the fact that some groups of elements seemed to have similar properties. For example, lithium, sodium, and potassium were soft shiny metals, easily tarnished in air. Their compounds were similar. Sodium chloride, table salt, is a salty tasting white crystal which dissolves easily in water. Lithium chloride and potassium chloride have the same properties.

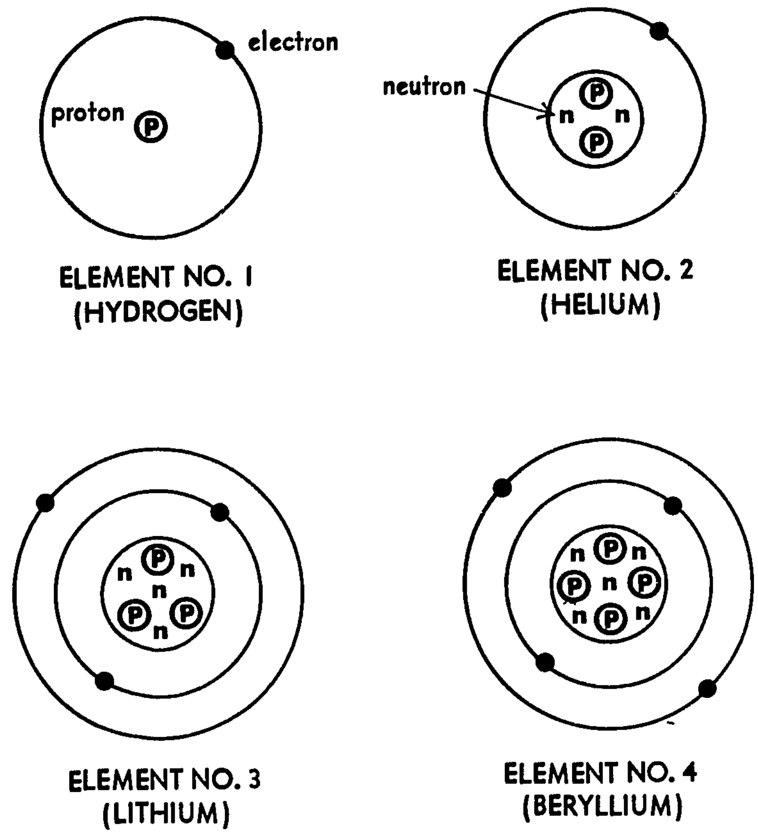


FIGURE 1.6.—Atoms of First Four Elements.

Mendeleev, in 1869, arranged elements in a pattern called the Periodic Table (see Table 1.1). This grouped together similar elements and enabled the prediction of new elements and even the properties of new elements which were then unknown. Using this table, the structure of the nucleus and the electron shells for an atom may be visualized. Also the atomic number and weight may be found.

The structure of the atoms of several elements may been seen in Table 1.1. Note that the atomic number tells how many protons, or positive unit charges, are in the nucleus and how many electrons, or negative unit charges, are in the shells about the nucleus.

1–9 Isotopes

Atoms of an element are composed primarily of electrons, protons, and neutrons. The protons and neutrons are particles having approximately the same mass, and they make up the nucleus of the atom. The electrons are arranged in shells about the nucleus and at a relatively long distance from the nucleus. The number of protons in the nucleus (the atomic number) equals the number of electrons in shells about the nucleus. This number determines the chemical properties of an element. The total number of protons and neutrons in the nucleus (the atomic weight) primarily determines physical properties of an element.

Thus, all atoms with one proton in the nucleus are hydrogen. All atoms with 8 protons are oxygen and all atoms with 27 protons are cobalt. If the number of protons in the nucleus of an atom is changed, the resulting atom will be a different element. The number of protons in atoms varies from one in hydrogen to 92 in uranium. Atomic work during and since World War II has resulted in producing several new elements which have atoms with more than 92 protons.

The number of electrons in orbit about the nucleus of an atom ordinarily equals the number of protons in the nucleus of the atom. By a process called ionization, the number of electrons may be changed but not the nucleus. It remains an atom of the same element as it was originally.

The number of neutrons in the nuclei of atoms ranges from zero for the hydrogen atom to 146 for uranium. In Figure 1.6 it may be seen that the nucleus of a hydrogen atom contains one proton and no neutrons. The next element, helium, has an atom containing 2 protons and 2 neutrons. Thus, it is said that hydrogen has an atomic weight of one and helium has an atomic weight of four. Is there anything with an atomic weight in between these?

Scientists found what was thought to be a sample of a pure element containing identical atoms. This was really a mixture of atoms with different atomic weights. These atoms had the same number of protons in their nuclei but had different numbers of neutrons. The atoms retained the same chemical properties while differing in atomic weight. These atoms of the same element having different numbers of neutrons were called *isotopes* of the element.

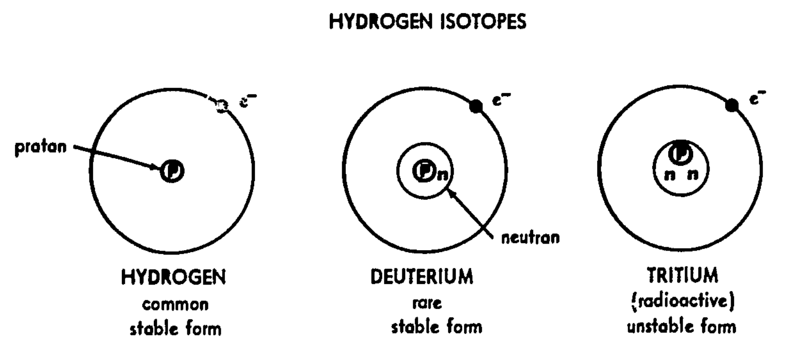


FIGURE 1.7.—Isotopes of Hydrogen.

Hydrogen was found to have two isotopes other than the ordinary hydrogen atom. By cooling hydrogen gas to a liquid and allowing it to evaporate, a concentration of heavier atoms remained. The nucleus of the "heavy" hydrogen (deuterium) atom contains a neutron as well as the usual proton. Heavy hydrogen atoms combine with oxygen to form "heavy" water. Only about one hydrogen atom in 14,000 is a heavy atom. More recently a still heavier hydrogen atom (tritium) has been discovered.

The number of isotopes for each element varies. While hydrogen has three isotopes, tin has 25 isotopes. Uranium has several isotopes. One is called uranium–238. Its nucleus has 92 protons and 146 neutrons for a total of 238 particles. Another isotope, uranium–235, has 92 protons and 143 neutrons, or 235 particles. Both of these react chemically in the same way. In all, more than 1,500 isotopes have been found. About 900 of these isotopes are *radioactive*. This means they are unstable and they will change in some way to attain a stable condition.

Table 1.1.—Periodic Table of Elements.

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	INERT GASES
1 Hydrogen H 1.008																	2 Helium He 4.003
3 Lithium Li 6.94	4 Beryllium Be 9.01											5 Boron B 10.8	6 Carbon C 12.0	7 Nitrogen N 14.0	8 Oxygen O 16.0	9 Fluorine F 18.9	10 Neon Ne 20.1
11 Sodium Na 22.9	12 Magnesium Mg 24.3											13 Aluminum Al 26.9	14 Silicon Si 28.0	15 Phosphorus P 30.9	16 Sulfur S 32.0	17 Chlorine Cl 35.4	18 Argon A 39.9
19 Potassium K 39.1	20 Calcium Ca 40.1	21 Scandium Sc 44.9	22 Titanium Ti 47.9	23 Vanadium V 50.9	24 Chromium Cr 51.9	25 Manganese Mn 54.9	26 Iron Fe 55.8	27 Cobalt Co 58.9	28 Nickel Ni 58.7	29 Copper Cu 63.5	30 Zinc Zn 65.3	31 Gallium Ga 69.7	32 Germanium Ge 72.5	33 Arsenic As 74.9	34 Selenium Se 78.9	35 Bromine Br 79.9	36 Krypton Kr 83.8
37 Rubidium Rb 85.4	38 Strontium Sr 87.6	39 Yttrium Y 88.9	40 Zirconium Zr 91.2	41 Columbium Cb 92.9	42 Molybdenum Mo 95.9	43 Technetium Tc (99)	44 Ruthenium Ru 101.1	45 Rhodium Rh 102.9	46 Palladium Pd 106.4	47 Silver Ag 107.8	48 Cadmium Cd 112.4	49 Indium In 114.8	50 Tin Sn 118.6	51 Antimony Sb 121.7	52 Tellurium Te 127.6	53 Iodine I 126.9	54 Xenon Xe 131.3
55 Cesium Cs 132.9	56 Barium Ba 137.3	57 Lanthanum La 138.9	72 Hafnium Hf 178.4	73 Tantalum Ta 180.9	74 Tungsten W 183.8	75 Rhenium Re 186.2	76 Osmium Os 190.2	77 Iridium Ir 192.2	78 Platinum Pt 195.1	79 Gold Au 196.9	80 Mercury Hg 200.5	81 Thallium Tl 204.3	82 Lead Pb 207.1	83 Bismuth Bi 208.9	84 Polonium Po 210	85 Astatine At (211)	86 Radon Rn 222
87 Francium Fr (223)	88 Radium Ra 226	89 Actinium Ac 227															

Lanthanum Series	58 Cerium Ce 140.1	59 Praseody- mium Pr 140.9	60 Neodymium Nd 144.2	61 Promethium Pm (145)	62 Samarium Sm 150.3	63 Europium Eu 151.9	64 Gadolinium Gd 157.2	65 Terbium Tb 158.9	66 Dysprosium Dy 162.5	67 Holmium Ho 164.9	68 Erbium Er 167.2	69 Thulium Tm 168.9	70 Ytterbium Yb 173.0	71 Lutetium Lu 174.9
Actinium Series	90 Thorium Th 232	91 Protactinium Pa 231	92 Uranium U 238	93 Neptunium Np (237)	94 Plutonium Pu (242)	95 Americium Am (243)	96 Curium Cm (245)	97 Berkelium Bk (249)	98 Californium Cf (249)	99 Einsteinium Es (254)	100 Fermium Fm (252)	101 Mendelevium Md (256)	102 Nobelium No (253)	103 Lawrencium Lw (257)

Chapter 2

Radiation and Radiation Machines

2–1 Radioactivity

At about the turn of the century, it was found that the material containing uranium gave off some kind of radiation that penetrated or passed through ordinary materials. Also, Roentgen discovered that something came off the anode of a Geissler tube and passed through the glass. Whatever this was caused a zinc sulfide screen held outside the tube to become fluorescent. He called the things that were given off "X-rays" because they were unknown to him. He knew they were not electrons since electrons cannot pass through glass or even a few sheets of paper.

Becquerel, in 1896, discovered that some radiation from certain minerals could fog photographic plates. Study revealed that those minerals containing uranium could give off this radiation that could pass through ordinary materials. The Curies found that minerals containing uranium and thorium were radioactive and that the radioactivity was proportional to the amount of these elements present. Later they found that pitchblende, an ore existing in the earth's crust, though containing uranium, gave off more powerful rays than uranium alone. Several years of work resulted in the discovery of the new element, radium. Further experiments resulted in the discovery of still more radioactive elements. What were these rays that such elements gave off?

2–2 Discovery of Radiation

Ernest Rutherford played an important role in discoveries about radiation. Experiments such as that illustrated in Figure 2.1 aided him in determining the nature of radiation. Suppose a bit of radioactive material, such as the element radium, is placed in a lead container with a long round opening. The radiation from the material would travel up the opening in a narrow beam. If a zinc sulfide screen is placed in front of the opening, the radiation beam causes a small circle to glow on the screen.

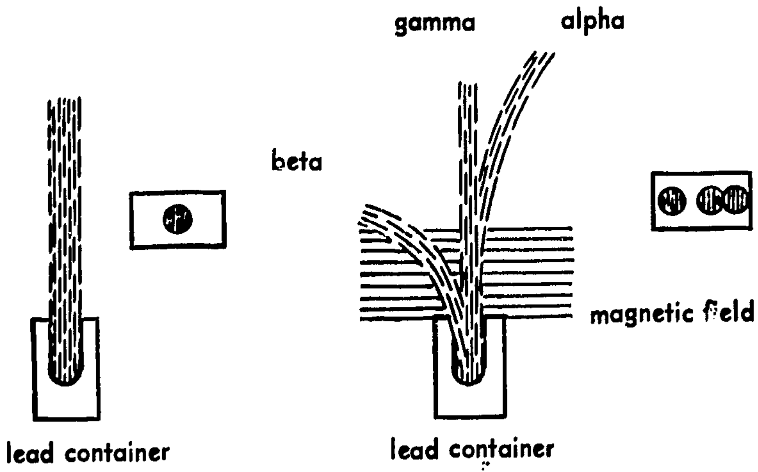


FIGURE 2.1.—Identifying Three Common Types of Radiation.

If a strong magnet is brought near the beam, there will be three spots glowing on the zinc sulfide screen. Each glows less intensely than the single spot. If the magnet is removed, the single spot reappears as before. The magnetic field caused the radiation beam to split into three beams. There is one beam on either side of the original beam. It seems that perhaps three different kinds of rays are given off by the radioactive material. These were called *alpha* (α), *beta* (β), and *gamma* (γ) rays.

Further experimentation showed that the alpha rays were deflected in such an angle as to indicate a positive charge. Since they were only deflected slightly, it would seem that the rays were probably composed of relatively heavy particles with a positive charge. Rutherford and others found the alpha particles to weigh about four times as much as the hydrogen atom. The inert gas, helium, has an atomic weight of 4. Thus, the alpha particle turned out to be the nucleus of a helium atom.

The beta rays were deflected in the opposite direction to show a negative charge. Since the amount of the deflection was much greater, it would seem probable that beta rays were lightweight negatively charged particles. These turned out to be electrons, the same kind that flowed from the cathode of the Geissler tube.

The undeflected gamma rays were not charged particles, but had the same characteristics as X-rays, discovered earlier.

Thus it was found that the atoms of radium and other radioactive elements are continually emitting alpha particles, beta particles, and/or gamma rays. Experiments determined the particles were given off at very high velocities, which was evidence of great amounts of energy locked up in the atom.

2–3 Kinds of Radiation

It should be clear now that there are two main types of radiation. One type is composed of tiny particles which move through space and is called "particulate" radiation. The other type consists of very short waves called "electromagnetic" radiation. Both of these kinds of radiation may be given off by radioactive atoms. Radioactivity refers to the disintegration of unstable nuclei of atoms. Both kinds of radiation convey energy through space.

Particulate radiation is the movement of tiny subatomic particles through space. The particles have mass (or weight) and, in most cases, an electrical charge. They transfer energy from one point to another. These particles traveling at a very high speed may strike and be deflected by other particles such as orbital electrons or nuclei of atoms, or they may be stopped and captured by nuclei. As these particles change speed, they change in energy. When they are slowed or stopped, they release energy. When particles carry an electrical charge, electrical or magnetic forces affect their motion. When these fast moving particles transfer energy to atoms, they may cause heat and light to be given off and they may cause ionization to take place. The particulate radiation of concern to isotope applications includes alpha and beta particles and neutrons.

Electromagnetic radiation consists of very short electromagnetic waves of energy having no mass or weight. The radiation moves with the speed of light (186,000 miles per second). Actually, electromagnetic radiation has been described as small packages of energy called photons or quanta. In this respect, such radiation has some properties of particles. However, electromagnetic radiation has a characteristic wave motion and wavelength, and its frequency can be determined. Frequency is measured in number of waves per second and wavelength is the distance between similar points on the waves. For all electromagnetic radiation, the product of frequency and wavelength is a constant. This constant is the speed of light. Also, the energy possessed by the photons or quanta depends on the frequency or wavelength of the radiation. High frequency radiation has high energy, while low frequency radiation has low energy. Thus, gamma radiation, which has very high energy (high frequency or short wavelength), penetrates matter much farther than does lower frequency ultraviolet radiation. The kinds of electromagnetic radiation of concern to us include X- and gamma radiation.

2–4 Properties of Radiation

Atoms and subatomic particles have been given an "atomic weight" determined by a weight comparison with the carbon atom. Remember that the carbon atom was arbitrarily given an atomic weight of 12. Usually, approximations of the atomic weights are given, though they have been determined by many accurate measurements to many decimal places.

Electrical charges and energy levels are given in descriptions of radiation. An electron is said to have a unit negative electrical charge. (This has been measured to be 4.80×10^{-10} electrostatic units.) A proton has a unit positive charge. The energy of radiation is expressed in ev's (electron volts). This is the energy (equivalent to 1.6×10^{-12} erg) acquired by a particle carrying a unit charge when it falls through a difference in potential of one volt.

Alpha radiation consists of relatively heavy particles, each containing 2 protons and 2 neutrons. The particles are identical with helium nuclei, except for their motion. When an alpha particle slows down in its passage through matter, it acquires two free electrons and becomes an atom of helium. An alpha particle has an atomic weight of 4.00277 and carries two unit positive electrical charges. Alpha particles are emitted from radioactive materials at speeds of 2,000 to 20,000 miles per second. Because of their size and relatively low speeds, they travel only a few centimenters in air and may be stopped by a sheet of paper. These particles are emitted with an energy ranging from 4 to 10 million electron volts (Mev).

Beta radiation consists of particles identical to high speed electrons. These particles carry one unit negative charge and have a mass about 1/1,840, that of a proton. They are emitted at very high velocities approaching the speed of light. They have a range of several feet in air but may be stopped by a thin sheet of aluminum or a few sheets of paper. The energy of beta particles ranges up to 3.15 Mev, with most particles having about 1 Mev.

Gamma radiation consists of very short electromagnetic waves of energy having no mass or weight. It has very short wavelengths of about 10^{-10} centimeters and extremely high frequencies and high energy. The radiation travels at the speed of light. These rays are highly penetrating and may be detected after passing through several inches of steel. The energy of gamma rays is measured in Mev. Gamma rays emitted by natural radioactive elements have energies from about 0.04 to 3.2 Mev.

X-rays and gamma rays are similar in that both are electromagnetic radiation. However, they differ in their origin. When the nucleus of a radioactive atom emits an alpha or beta particle, the daughter nucleus frequently is left in a high energy or excited state and the excess energy is emitted as gamma radiation to bring the nucleus to a more stable condition. Thus, gamma radiation originates in the nucleus of an atom.

X-rays, on the other hand, are produced when any stream of fast-moving (high-energy) electrons is slowed down upon striking a suitable target. Electron transitions between orbital shells give rise to the photons or quanta of energy called characteristic X-rays.

The neutron is another type of particle which accompanies certain types of nuclear reactions. It is not found in natural radioactive decay, however. The neutron particle has about the same mass as a proton but is neutral so far as electrical charge is concerned. It was found that when alpha particles bombarded light elements such as beryllium and lithium, they emitted neutrons. Because neutrons have no electrical charge, they make good "bullets" to bombard the nuclei of elements. The positively charged nuclei do not repel the neutron as they do other particles. Neutrons play an important role in nuclear fission, since the capture of a neutron by nuclei of atoms of certain elements causes the nuclei to split apart and form atoms of different elements.

A number of particles and radiation have been identified. A list of the properties of some particles and radiation is presented in Table 2.1.

TABLE 2.1.—Properties of Nuclear Radiation

Radiation		Kind	Mass	Charge	Description
Alpha	(α)	Particle	4	+2	Helium Nucleus
Beta	(β)	Particle	1/1840	±1	High Speed Electron
Gamma	(γ)	Wave	0	0	Electromagnetic Wave
Neutron	(n)	Particle	1	0	Uncharged Particle

2–5 The Electromagnetic Spectrum

Radiation or *radiant energy* is of great concern in modern atomic study. Light and radio waves are the most familiar forms of electromagnetic radiation. These are seemingly very different kinds of radiation. Energy from the sun comes to the earth mainly as light. However, it is known that what is called "sunlight" contains radiant energy that is invisible. This may be infrared radiation or ultraviolet radiation. In a similar fashion, radio waves are a transfer of energy through space. This is invisible radiation and usually the amount of energy picked up by a distant receiver is small.

Many experiments have verified the wave motion property of light and radio waves. A wave motion consists of a series of crests and troughs. The distance between any two successive crests or troughs is called the *wavelength* of the radiation and is usually designated by the Greek letter *lambda* (λ). Now, if C designates the speed of the radiation through space, then the number of waves passing a point in the unit of time will be C/λ and is called the *frequency* of the wave motion. This is usually designated by the Greek letter *nu* (ν). Thus it should be noted that frequency times wavelength equals the speed of propagation of radiation.

$$\text{frequency} \times \text{wavelength} = \text{speed}$$
$$\nu \times \lambda = C$$

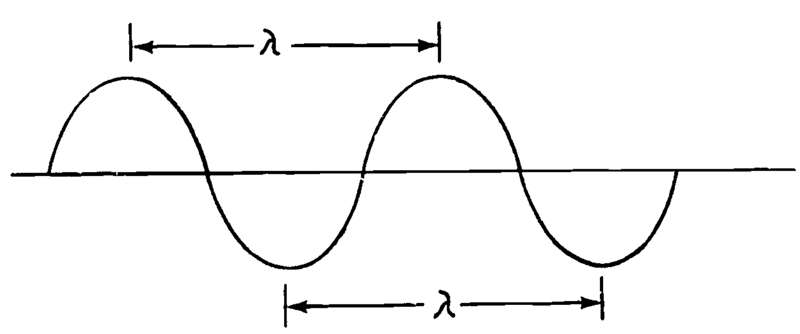


FIGURE 2.2.—Wave Motion and Wavelength (λ).

It is known that light, radio waves, and other radiation called *electromagnetic* radiation travel at a speed depending on the medium through which they pass. The speed usually given is that for empty space. When measured in air, a small correction is made. The radiation travels at about 186,000 miles per second, an extremely high velocity. For scientific work, this is usually stated in centimeters per second and is rounded to 3.00×10^{10} centimeters per second.

There are electromagnetic radiations having wavelengths both longer and shorter than light. At one extreme are the long radio waves with wavelengths of hundreds of meters. Near the other extreme are the gamma rays and X-rays with wavelengths on the order of 10^{-10} centimeters.

They found that, if nitrogen is bombarded by alpha particles, a proton or hydrogen nucleus is formed as well as an isotope of oxygen. Thus, the concept of "atom smashing" was begun.

$$_7N^{14} + {}_2He^4 \rightarrow {}_1H^1 + {}_8O^{17}$$

In only a few cases, however, is the nucleus actually disintegrated. Usually there is simply a rearrangement of protons and neutrons among the nuclei concerned. The terms "nuclear transformation" or "transmutation" are preferred. Such changes may be called "artificial" to distinguish them from naturally occurring nuclear changes.

Early experiments in transmutations were carried out with alpha particles available from naturally occurring radioactive materials.

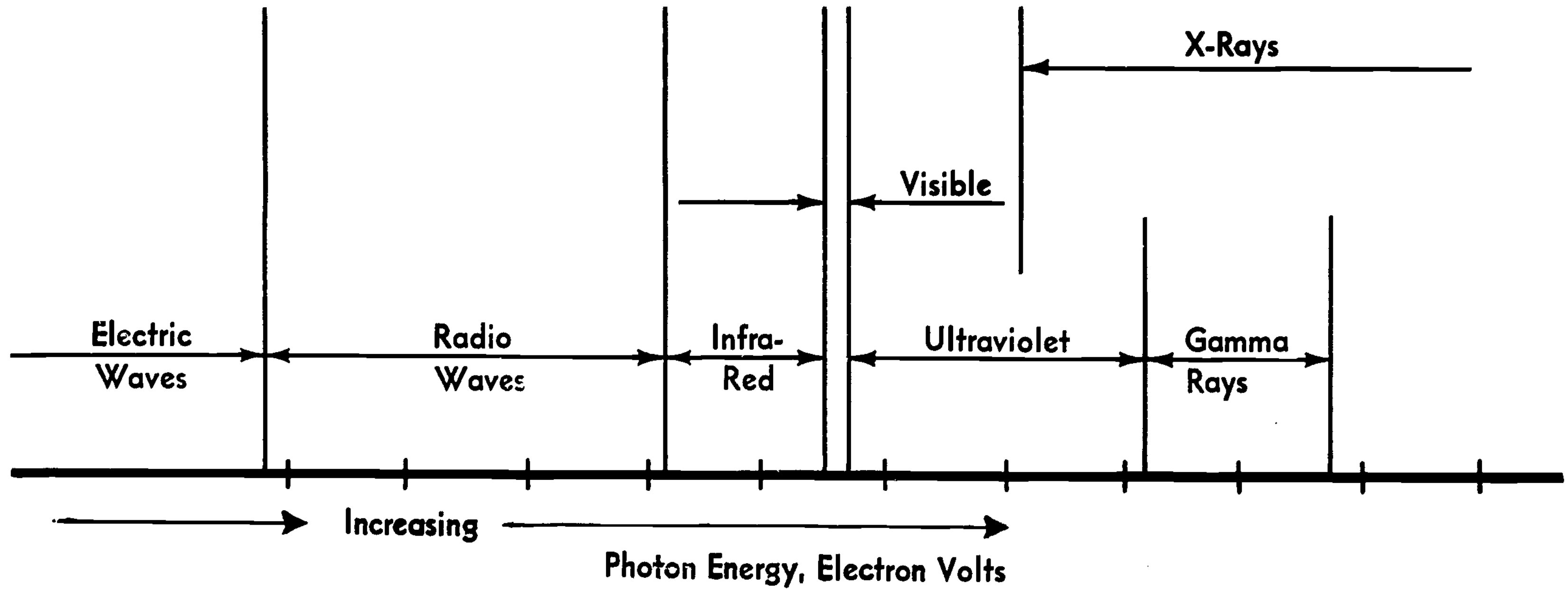


FIGURE 2.3.—The Electromagnetic Spectrum.

The electromagnetic spectrum is a continuous band of radiation with a gradual shift from one type of radiation to another. Thus, the longer gamma rays are identical with the shorter X-rays. Also, the shorter radio microwaves are the same as the long infrared waves. There is no sharp division between different "kinds" of electromagnetic radiation.

2–6 Radiation Machines

In the early 1900's, it was speculated that the nucleus of an atom could be altered by direct collision with high speed particles. These include electrons and alpha particles such as those emitted by radioactive materials. Rutherford and Chadwick in the 1920's performed a number of experiments which confirmed this. When calculations indicated that perhaps other charged particles might be more effective as "bullets" to cause nuclear rearrangement, scientists began to think about building high voltage machines to accelerate protons and other particles. Brief descriptions of some of these machines and the X-ray machine follow.

2–6.1 *Van de Graaff Generator.* The Van de Graaff is an electrostatic, straight-line accelerator. Electrons, protons, deuterons, and alpha particles are commonly accelerated in a Van de Graaff machine, but other charged particles may be used. A moving belt is used to transfer charges to an insulated hollow metal sphere. In this way potentials of several million volts can be developed. This potential is used to accelerate charged particles down a tube to a target.

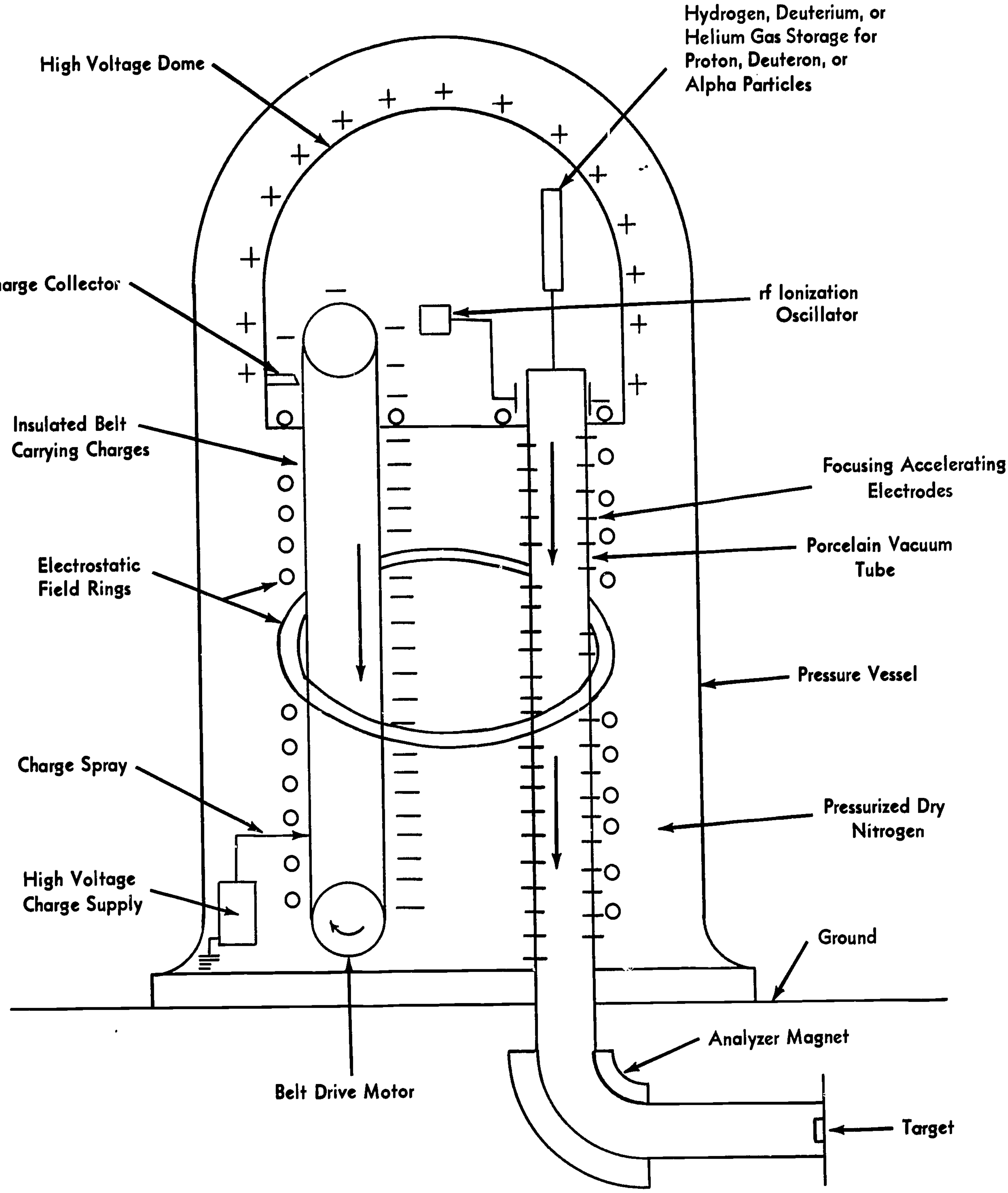


FIGURE 2.4—Van de Graaff Generator.

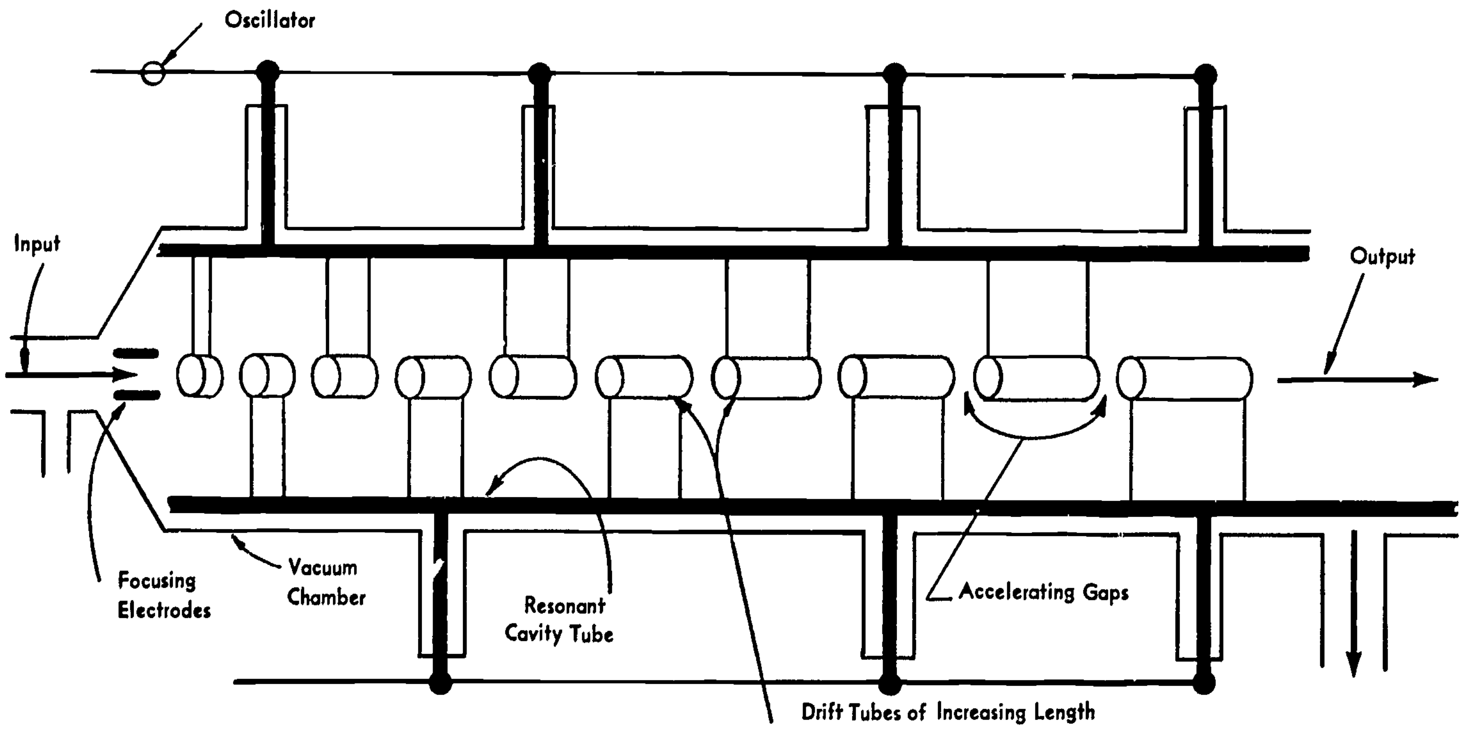


FIGURE 2.5.—Linear Accelerator.

2–6.2 *Linear Accelerator.* This machine consists of a number of cylinders of increasing lengths. Alternate cylinders are connected together. Thus, numbers one, three, and five are connected to one terminal of a high-frequency oscillator, and numbers two, four, and six are connected to the other terminal. At any particular instant, alternate cylinders carry opposite electrical potentials. On any half-cycle of the oscillator, for example, the odd-numbered cylinders may have a positive charge and the even-numbered cylinders may carry a negative charge. Positive particles passing through the first cylinder receive no acceleration, but, upon reaching the gap, there is a difference in potential and they are accelerated across the gap. If the lengths of cylinders are correct, the positive particle receives an accelerating impulse at each gap. The target is at the end of the last cylinder. In these machines, electrons may be accelerated to a velocity approaching the speed of light. Fast particles produced by these machines are used to study nuclear structure and nuclear reactions, to produce radioisotopes, and to provide a source of X-rays and neutrons.

2–6.3 *Betatron.* The betatron is an electron accelerator which uses magnetic induction to accelerate electrons in a circular path. A varying magnetic field is used to provide the orbital acceleration. This is provided by a large, laminated iron core in a transformer with the magnet coils operating on various frequencies. Electron velocities are high and the electrons make many revolutions acquiring high energies in a very short time. When these high speed electrons bombard the target, X-rays are emitted. (Figure 2.6)

2–6.4 *X-ray Tubes.* There are wide differences in the structure of X-ray tubes. Some are air-cooled and some are oil-cooled. Some have a stationary anode while others have a rotating anode. All tubes have an electron generating filament and a target anode enclosed in a high vacuum. A positive charge is placed on the anode or target so that the negative electrons are attracted. When they strike the anode and are slowed down, they release some energy in the form of X-rays. This is usually referred to as general X-radiation and covers a relatively wide band of wavelengths (these wide bands of X-rays are often called "white," "continuous" or "heterogeneous"). The high speed electrons also dislodge orbital electrons in the target material. Energy is imparted to the atom in removing the electron. The excited atom attracts an electron and returns to a stable state. Its extra energy is then emitted as a form of X-radiation. This is a narrow band of X-radiation, the wavelength of which is determined by the target material and the orbital location of the dislodged electron.

X-ray tubes require a high voltage electric circuit to supply a positive potential to the anode. These range up to millions of volts. Also, a filament circuit is required to heat the electron-emitting filament of the tubes. These machines have a wide range of use, ranging from medicine to industry. (Figure 2.7)

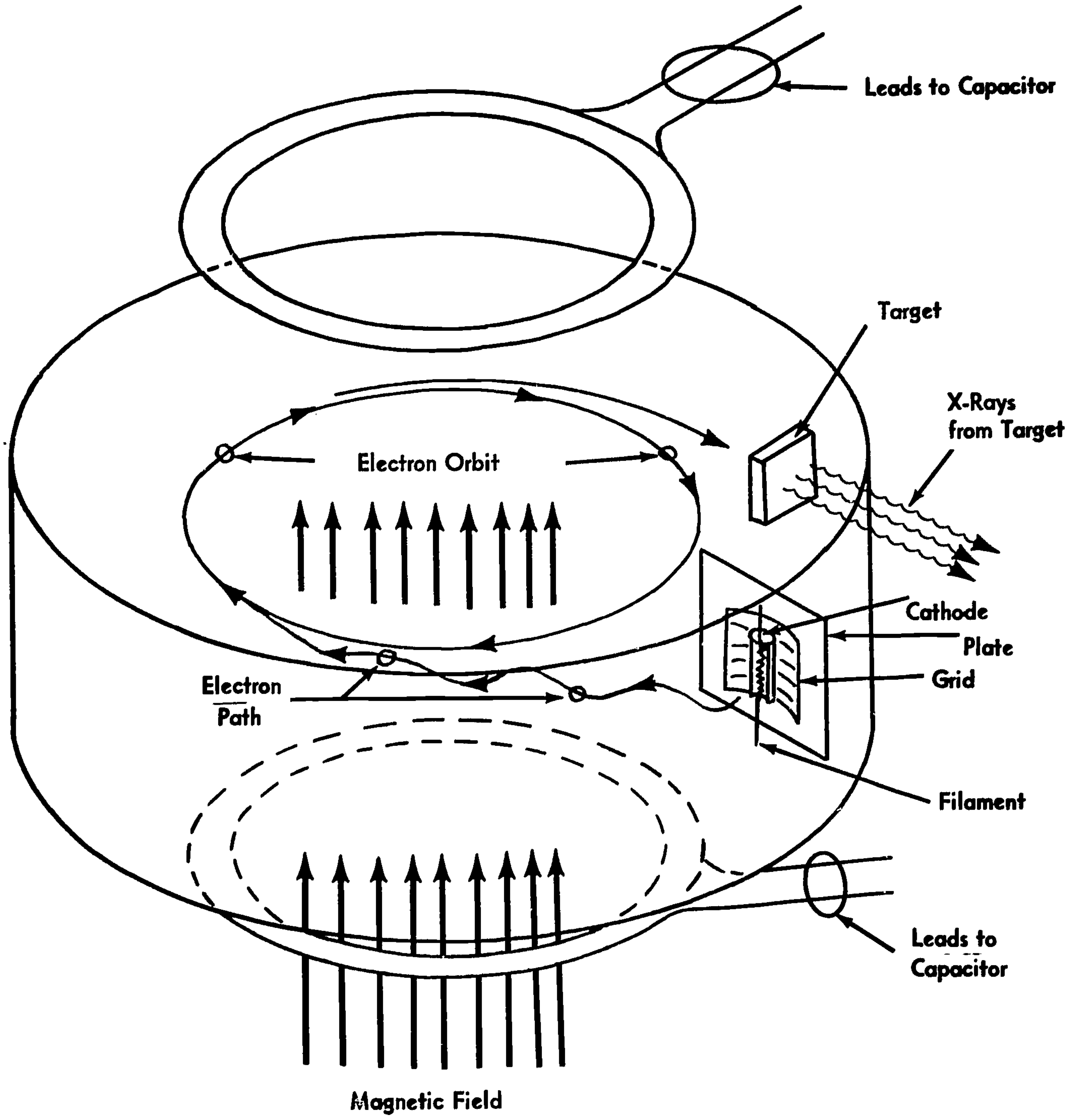


FIGURE 2.6.—The Betatron.

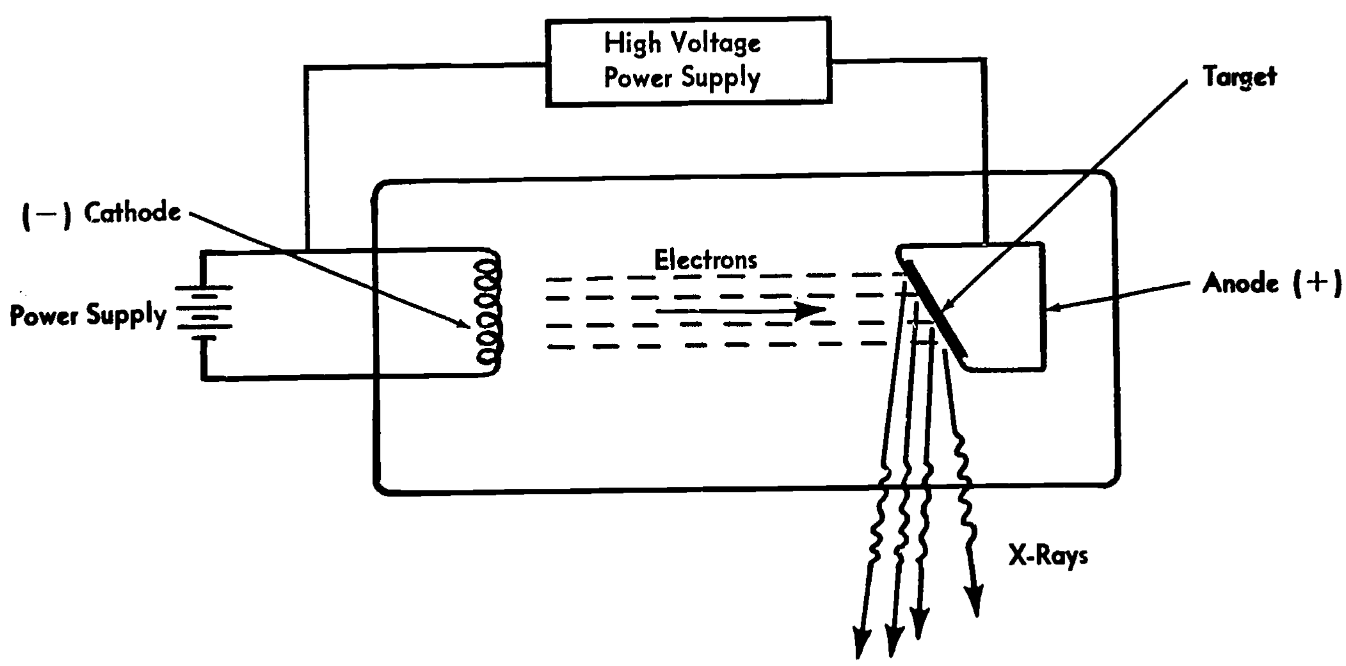


FIGURE 2.7.—The X-ray Machine.

Chapter 3

Nuclear Reactions and Radioisotopes

3–1 Nuclear Reactions

Radioactive atoms which emit one or more particles, and perhaps some energy in the form of gamma rays, have been described. Another type of nuclear reaction results when the nucleus of an atom actually splits into two almost equal portions. In such a reaction neutrons and, in some cases, protons are emitted. This type of reaction is called *fission.* Large amounts of released energy accompany the fission of nuclei. The nucleus of each atom is held together by a force called *binding energy.* The heavy nucleus which is *fissionable* has more binding energy than the two lighter atoms formed after the fission; therefore, energy is given up.

When two light nuclei come together to form a heavier nucleus, the process is called *fusion.* This type of nuclear reaction also gives up energy. Here, as in the fission process, there is a loss of mass in the form of energy. This kind of reaction can be initiated only by heating to extremely high temperatures. By use of nuclear fission, these temperatures can be reached. Once started, the thermonuclear reaction generates enough heat to sustain a chain reaction.

3–2 Nuclear Fission

Physicists have long been interested in the structure of matter. The nucleus of the atom has been of much interest. Early efforts to study the nucleus have involved the bombardment of matter with alpha particles, protons, and deuterons. Also of interest was the matter of the release of energy. One early experiment involved directing a stream of protons at the metal lithium. From the lithium came alpha particles. It was found that for each proton that hit a lithium nucleus, there appeared two alpha particles. A lithium nucleus has a charge of 3 and a mass of 7. A proton has a charge of 1 and a mass of 1. The process is illustrated as follows:

$$_{3}Li^{7} + {}_{1}H^{1} \rightarrow {}_{2}He^{4} + {}_{2}He^{4}$$

The lithium nucleus has 3 protons and 4 neutrons. When it takes up a proton, it then has 4 protons and 4 neutrons and is in a very unstable condition. It immediately breaks and forms two helium nuclei (alpha particles), each with 2 protons and 2 neutrons. Because much energy is released, the two helium nuclei fly apart at great speed. It was found that the mass of the two helium nuclei was less than the mass of the lithium nucleus and the proton. Some mass had been converted into energy.

This is a very poor way to release atomic energy. A nucleus is very small compared to the rest of the atom, and a proton has a small chance of hitting a lithium nucleus. Also, since the proton and lithium nucleus are both positively charged, they repel each other. Only about one proton in 1,000 will hit a lithium nucleus.

In the 1930's, shortly after neutrons were discovered, Fermi used them to bombard nearly all the elements. Being electrically neutral, neutrons were not repelled by positively charged nuclei and more hits occurred. As a result, Fermi discovered a large number of new radioactive substances. Frequently, a nucleus would capture a neutron. This produced a nucleus with too much mass for its charge and hence an unstable one. The nucleus would emit a beta particle (electron) and return to a more stable state. However, the nucleus was now one mass unit and one positive charge higher than the parent nucleus and thus was a different element.

For example, cobalt is the 27th element with a mass of 59 units. Its symbol is $_{27}Co^{59}$. This means that the nucleus has 27 protons and 32 neutrons. The cobalt nucleus may capture a neutron to give cobalt–60. The process is written as follows:

$$_{27}Co^{59} + {}_{0}n^{1} \rightarrow {}_{27}Co^{60}$$

Cobalt–60 is a radioisotope of cobalt. This isotope emits gamma rays as it decays that make it commercially useful for radiography.

Fermi wondered what would happen if uranium was exposed to neutrons. In 1934, uranium was the 92nd or last element. If a uranium nucleus should capture a neutron, what would happen? The most stable and frequently found isotope of uranium has a mass of 238. Its symbol is ${}_{92}U^{238}$. When a nucleus of U–238 captures a neutron, the new atom emits a beta particle and becomes neptunium, the next heavier element after uranium.

$${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} + e^{o} \rightarrow {}_{93}Np^{239} + e^{o}$$

Neptunium is radioactive and also emits a beta particle to become element 94, plutonium.

$${}_{93}Np^{239} + e^{o} \rightarrow {}_{94}Pu^{239} + e^{o}$$

In both cases, a neutron in the nucleus has emitted an electron to become a proton.

U–235, an isotope of uranium, can capture slow neutrons and fission or break into two approximately equal fragments. Also, it was found that the new element plutonium would fission. Of great importance is the fact that the process of fission not only releases great energy, but also releases neutrons. These may, in turn, cause other nuclei to fission. When conditions are correct, such a process causes a *chain reaction* or self-sustaining fissioning of the material.

3–3 Chain Reactions and Criticality

In addition to U–235 and plutonium, it was found that elements 90 and 91, thorium and protoactinium, also were fissionable. When fissionable atoms split, it is into approximately equal fragments. These turn out to be isotopes of elements in the middle of the periodic table. When uranium–235 fissions, it has been found that barium and krypton are among the products formed. The process may be written as follows:

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{138} + {}_{36}Kr^{83} + 14{}_{0}n^{1} + \text{energy}$$

In Figure 3.1, what happens to the neutrons may be clearly seen. These released neutrons may be captured by other atoms of U–235 and cause more atoms to fission.

Because only a small amount of U–235 is contained in natural uranium, it was necessary to separate U–235 from the more plentiful U–238. This was necessary in order to have the U–235 fission process be self-sustaining. A self-sustaining fission process is called a *chain reaction.*

When the nucleus of a fissionable atom captures a neutron and splits, it has been shown that a great amount of energy is released. Also, a number of neutrons are emitted from the nucleus. If only one of these neutrons caused another atom to split, and only one neutron from that nucleus caused another atom to split, and so on, then the fission process would just maintain itself. When a piece of fissionable material such as U–235 or Pu–239 is below a certain size, more neutrons escape from the surface of the piece than are produced in fission. There are always enough stray neutrons in the atmosphere to cause some of the atoms to fission; however, an increasing chain reaction is not built up in a small piece of the material. When a mass is large enough (and of correct shape) so that a chain reaction is supported, it is called a *critical* mass. When several pieces are brought together to form a critical mass, then a nuclear explosion occurs. (Figure 3.2)

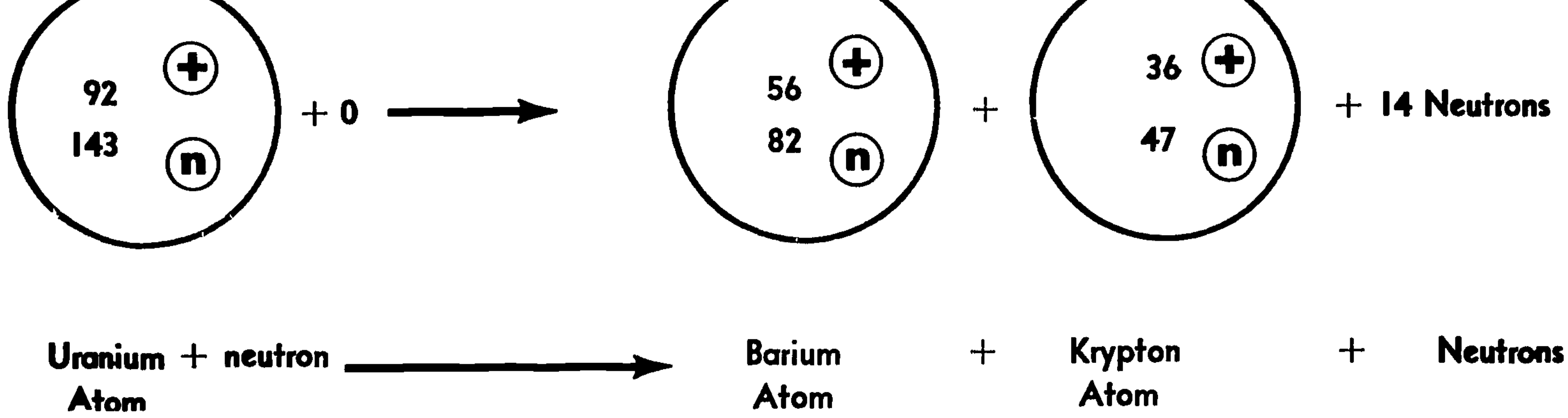
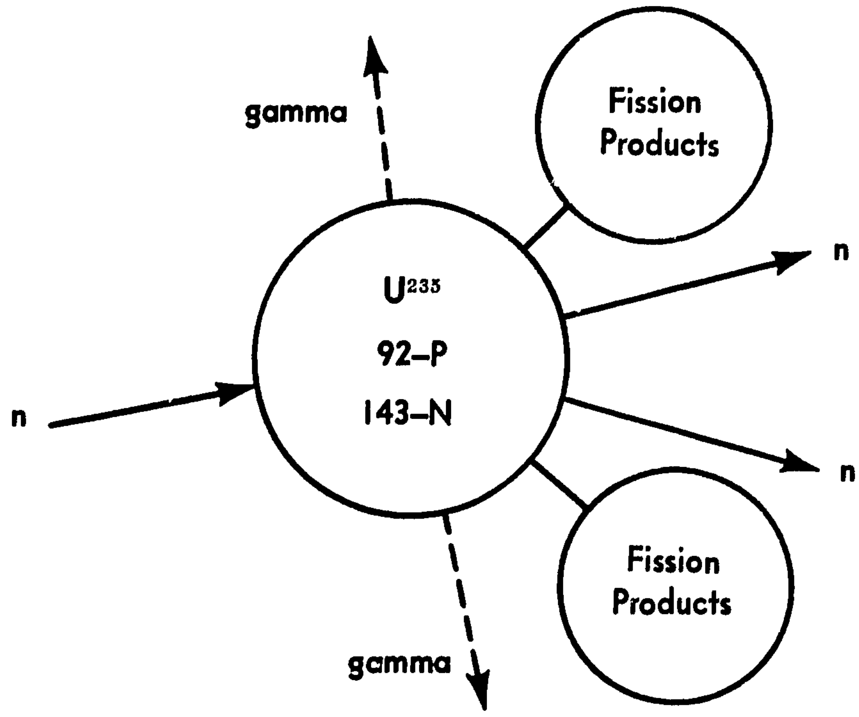


Figure 3.1.—Neutrons Released in Uranium Fission.



Fission of A Single Atom

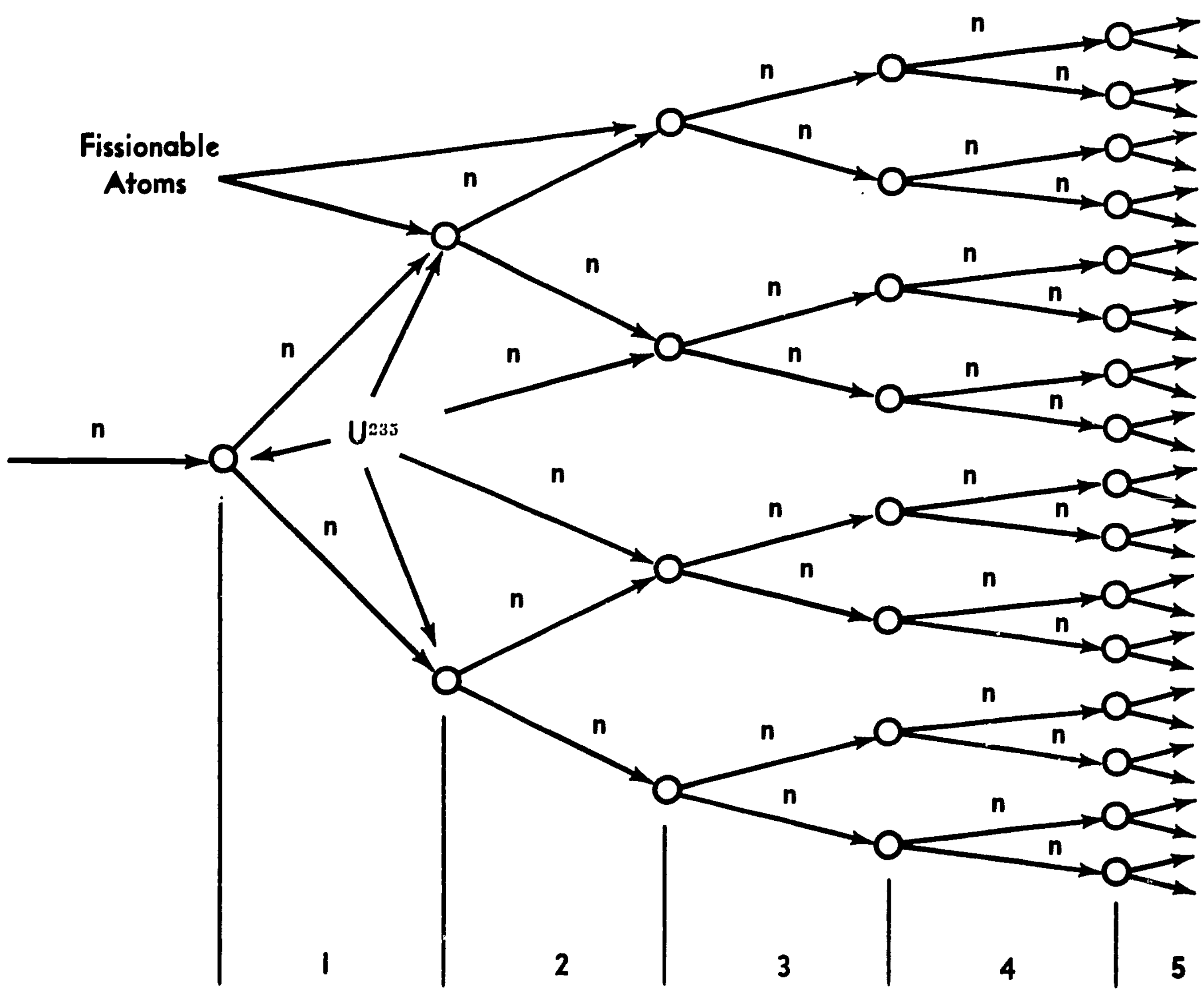


FIGURE 3.2.—Chain Reaction of U-235.

3–4 Fission Products

Uranium fission takes place in an unsymmetrical manner. The two nuclear parts have different masses. It is known that the two groups of fission particles cluster around isotopes of mass number 90 and 140. It has been mentioned that barium (Ba–138) and krypton (Kr–83) are frequently found fragments. Also found are strontium (Sr–90) and cesium (Cs–137).

Figure 3.3 shows how the fission fragments of U–235 cluster around the two mass numbers 90 and 140. More than 95 percent of the U–235 nuclei that fission give parts that fall into two groups. One is a light group with mass numbers from 85 to 104. The other is a heavier group with mass numbers from 130 to 149.

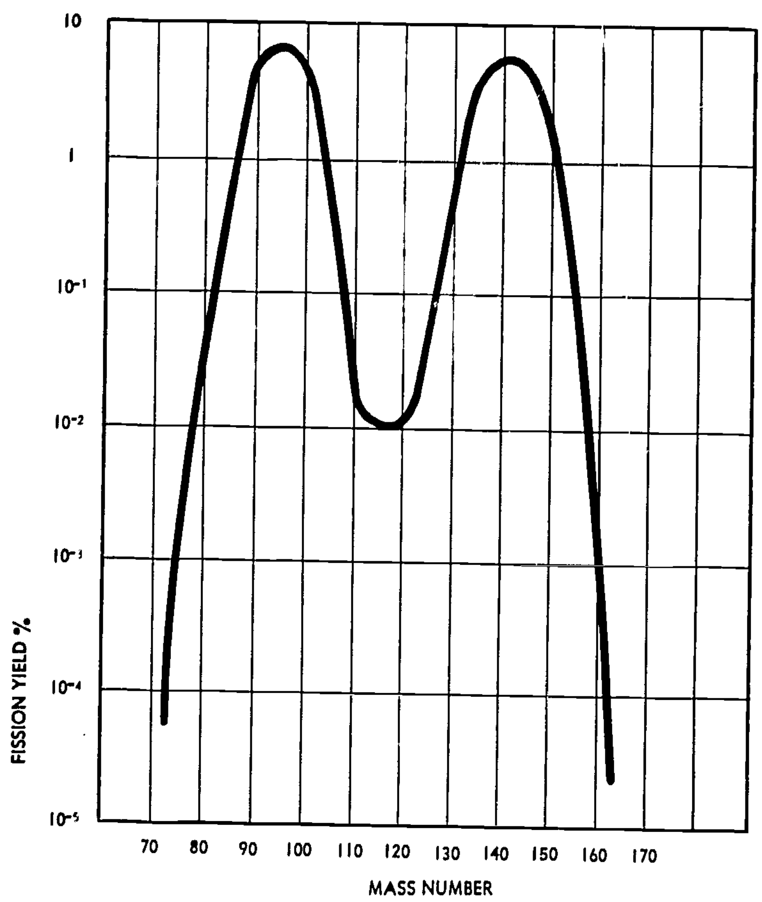


FIGURE 3.3.—Distribution of Fission Products.

The two parts of a fissioned U–235 nucleus may be seen to contain too many neutrons and so are usually unstable and emit neutrons. Most of these neutrons are emitted in an extremely short time after fission. Thus, a chain reaction in a critical mass of U–235 takes place in an extremely short time.

3–5 Activation of Isotopes

A few naturally occurring isotopes are radioactive, such as radium and uranium. Since the 1930's, however, a large number of isotopes have been obtained by scientists. Now, more than 1,500 isotopes are known, most of them radioactive. In fact, radioisotopes of all elements have been obtained. For example, there are radio-carbon, radio-cobalt, and radiocesium.

The early production of radioactive isotopes usually involved some kind of machine to shoot fast subatomic particles at atoms of the various elements. The cyclotron was an early device used to secure high-speed particles. Deuterons, alpha particles, and protons were used as *bullets* in the cyclotron.

Now, however, most radioisotopes are produced in nuclear reactors or chain-reacting piles. The fission reaction itself in a reactor produces some radioactive products. Another way is to insert a small mass of some element into the reactor pile and subject it to bombardment by neutrons.

Neutron absorption is a process that frequently leads to a radioactive isotope. For example, the stable cobalt isotope ${}_{27}Co^{59}$ may capture a neutron to become radioactive cobalt ${}_{27}Co^{60}$. This is done by inserting the Co–59 into a reactor and bombarding it with neutrons.

The *activation* of atoms bombarded by neutrons depends upon a number of factors. Among these are neutron density and the nuclear cross section of the nuclei being bombarded. The number of target nuclei being activated may be represented by the equation:

$$A = Nf\sigma t$$

where

A = number of target nuclei being activated
N = total number of nuclei in the target
f = neutron density per cm^2/sec
σ = nuclear cross section of target atoms (the probability that a neutron passing through the target material will be captured by a target nucleus)
t = time in seconds

As some nuclei capture a neutron and become radioactive, decay commences immediately. The buildup in number of radioactive nuclei continues until the rate of formation and the rate of decay are equal. After this point, there will be no change in the number of radioactive nuclei present in the target.

3–6 Nuclear Reactors

The first atomic pile, or nuclear reactor, was built by Enrico Fermi and other scientists at the University of Chicago in 1942. They wished to see if a chain reaction could be started that would keep itself going. The pile was made up of blocks of graphite. Small pieces of natural uranium in metal tubes were placed in holes in the pile of graphite blocks. The graphite acted as a *moderator* to slow down fast neutrons so more neutrons would enter U–235 nuclei and keep the chain reaction self-sustaining. In slots in the pile, pieces of cadmium metal were placed to control the reaction. Cadmium acts as an absorber of neutrons. When the cadmium strips are pulled out, the reaction speeds up. If the reaction becomes too fast and too much heat is generated, the strips are pushed back in the pile.

Fuels used in reactors are such fissionable materials as U–233, U–235, and Pu–239. Since the mass of the fission fragments and liberated neutrons is less than the original fissionable atoms plus the neutrons which started the fission, mass is not conserved and energy is liberated. The energy is given off as radiation and as kinetic energy imported to the fission fragments and fission neutrons. As the fission neutrons and fragments are slowed down and the radiation is absorbed in the surrounding materials, the fission energy is converted to thermal energy or heat.

A reactor is, therefore, a source of both heat and neutrons. When a reactor is used as a power plant, it is considered primarily as a source of heat energy. This energy is used then to convert water to steam and the steam is used to drive electrical generators. The extra neutrons may be used to produce more fissionable material from U–238 and Th–232 and to produce radioactive materials such as Co–60 or Cs–137.

The U–238 and Th–232 absorb neutrons and then decay into the highly fissionable isotopes Pu–239 and U–233, respectively. Thus, a reactor may act as a "breeder" to make new fuel and so on.

Co–60 and Cs–137 are used in industrial radiography as sources of radiation. Figure 3.4 shows how a reactor is used to create radioactive isotopes. For example, some stable Co–59 may be inserted in an opening in the reactor. As found in nature, cobalt has 27 protons and 32 neutrons, or a mass number of 59. When the stable cobalt is bombarded by billions of neutrons, some nuclei capture a neutron and then have 33 neutrons instead of 32. Cobalt 60 gives off strong gamma radiation, some beta radiation, and has a half-life of 5.3 years.

Radioisotopes are obtained by two principal methods:

(1) Fission products, that is the fission fragments formed when heavy nuclei split, are gathered and separated from the waste material in an atomic reactor.

(2) The bombarding of atoms with neutrons so that their nuclei capture neutrons and become radioactive without changing to another material or element.

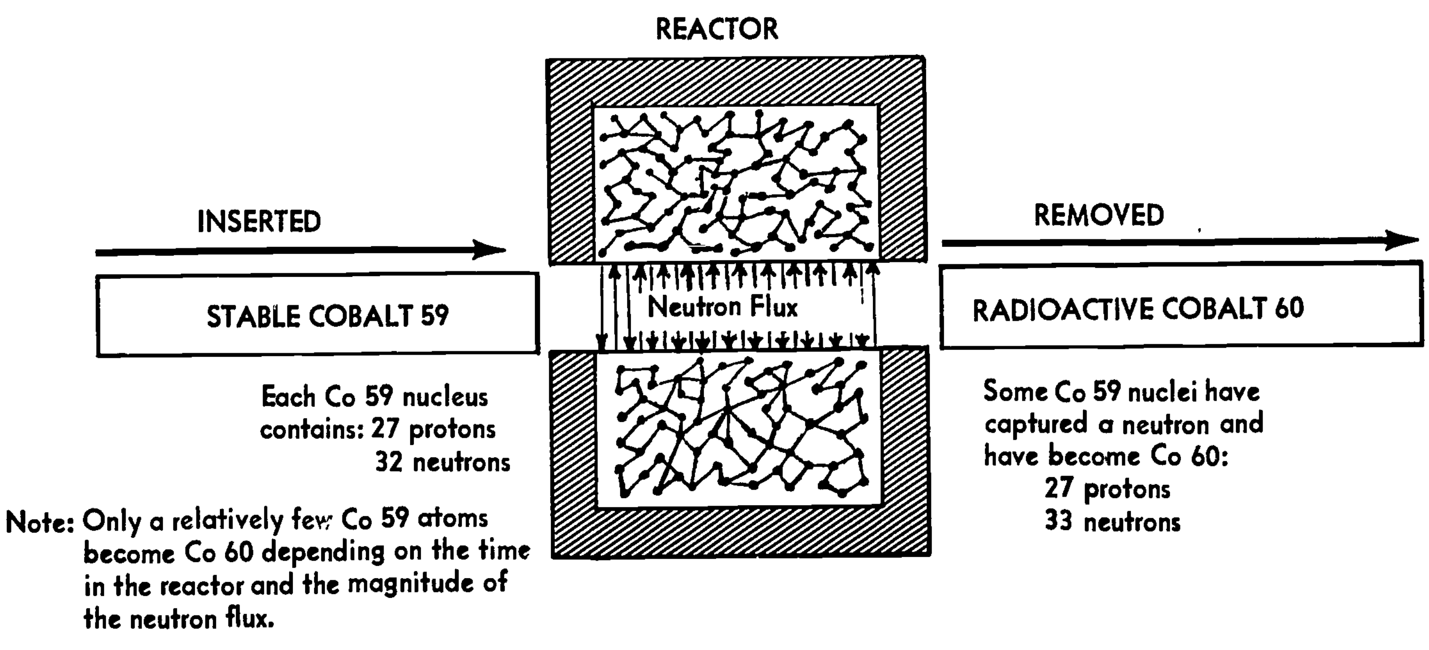


FIGURE 3.4.—Production of Cobalt-60.

3–7 Decay of Radioactivity

The nuclei of radioactive atoms are in an excited state or contain excess energy. The excess energy is emitted as radiation. The radiation usually takes the form of alpha or beta particles and gamma rays. The naturally occurring radioactive elements at the high atomic weight end of the periodic system fall into three rather distinct series. These are the *thorium*, the *uranium*, and the *actinium* series. Some radioisotopes, however, decay in one step to a stable state. The series may involve more than a dozen steps before resulting in a stable isotope. The resulting isotopes are called *daughter* products.

It is possible to follow one atom of uranium 238 through its series of disintegrations. An atom of U–238 has 92 protons and 146 neutrons. In Table 3.1, the decay is shown step by step as alpha and beta particles are emitted. The final stable product is lead–206 which has 82 protons and 124 neutrons. When an alpha particle is emitted, the atomic weight decreases by 4 because the atom loses 2 protons and 2 neutrons. However, when a beta particle is emitted, the atomic weight remains the same, but the atom changes to a new element. It was found experimentally that the number of atoms of a radioactive element which decay in a unit of time is proportional to the total number of atoms present at that time. Since decay is a continuous process, the total number of atoms present is changing and the rate of decay is changing. By use of calculus, an equation may be found to represent the decay which takes the following form:

$$N = N_0 e^{-\lambda t}$$

where

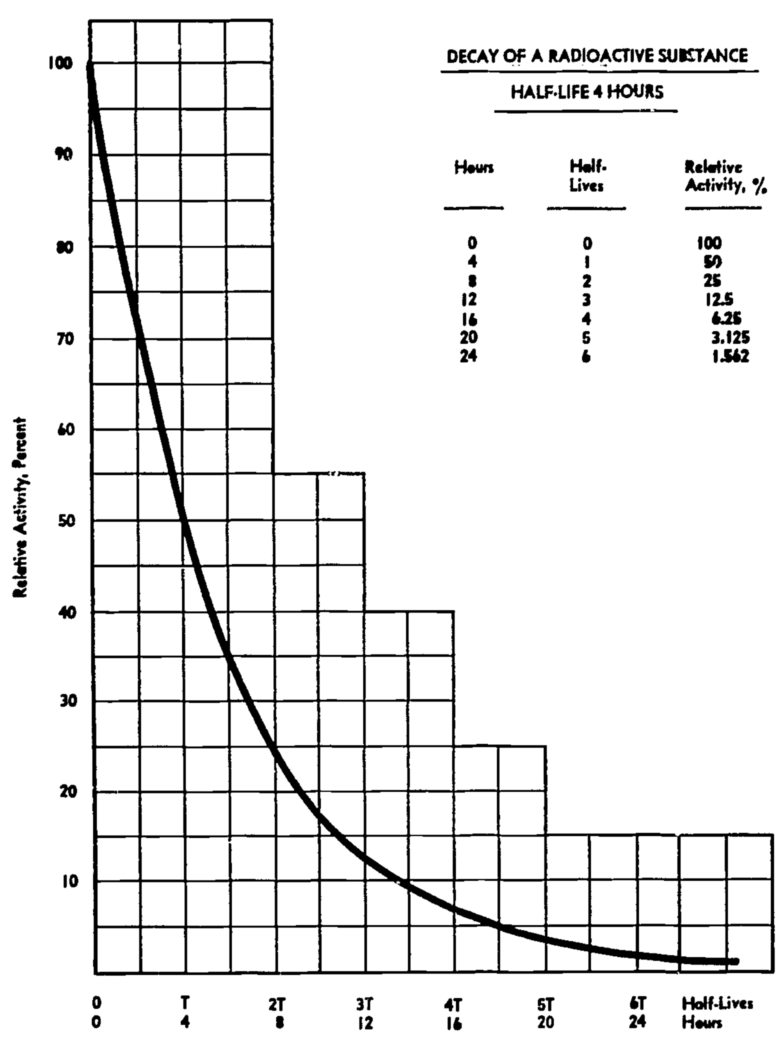
N_0 = number of atoms present at zero time

e = base of natural logarithms = 2.718 . . .

λ = decay constant of the radioisotope

t = time

N = number of atoms remaining after "t" time



Hours	Half-Lives	Relative Activity, %
0	0	100
4	1	50
8	2	25
12	3	12.5
16	4	6.25
20	5	3.125
24	6	1.562

FIGURE 3.5.—Decay of Radioisotopes.

The constant λ is related to a useful term, the half-life of a radioactive element. This is the length of time necessary for half of the atoms to decay.

$$\text{half-life} = \frac{0.693}{\lambda}$$

The half-life is useful as a characteristic of a radioisotope. From Figure 3.5, it may be seen that, after six half-lives, the amount of decaying atoms is reduced to less than 2 percent of the amount at the beginning.

3–8 The Curie

The number of disintegrations which a given amount of a radioisotope has during a given length of time is called the *activity* of the isotope. The unit of measure of activity is the *curie*. A curie is defined as the amount of any radioisotope that gives 3.7×10^{10} disintegrations per second. For some isotopes, this is a rather large amount of material, so the units, *millicurie* and *microcurie*, are commonly used.

(1) 1 curie = 1,000 millicuries

(2) 1 millicurie = 1,000 microcuries

3–9 Plotting Radioactive Decay

Each disintegration of a radioisotope may be supposed to result in the ejection of a single particle or photon. The rate at which these are expelled per second from a radioactive source may be measured by various detection devices which measure or count disintegrations. The count per unit of time may be plotted against time and a decay curve obtained.

For example, consider a small amount of Co-60. Let the radiation count on January 1, 1963 be 15,000 counts per minute. The half-life of Co-60 is 5.3 years. In Figures 3.6 and 3.7, the decay curve is plotted on cartesian coordinate paper and on semi-log coordinate paper. Note that during each 5.3 years the count will have decreased by one-half.

On the cartesian coordinate paper, the decay curve is an exponential curve, while on the semi-log paper the decay curve is a straight line. The advantages of plotting on semi-log paper are evident as only two points are needed to plot the decay curve.

THE URANIUM SERIES

Radioelement	Corresponding Element	Symbol	Radiation	Half Life
Uranium I ↓	Uranium	U^{238}	α	4.51×10^{9} yr.
Uranium X_1 ↓	Thorium	Th^{234}	β	24.1 days
Uranium X_2* ↓	Protactinium	Pa^{234}	β	1.18 min.
Uranium II ↓	Uranium	U^{234}	α	2.48×10^{5} yr.
Ionium ↓	Thorium	Th^{230}	α	8.0×10^{4} yr.
Radium ↓	Radium	Ra^{226}	α γ—.18	1.62×10^{3} yr.
Ra Emanation ↓	Radon	Rn^{222}	α	3.82 days
Radium A 99.98% | 0.02%	Polonium	Po^{218}	α and β	3.05 min.
Radium B	Lead	Pb^{214}	β γ—.35	26.8 min.
Astatine-218 ↓	Astatine	At^{218}	α	2 sec.
Radium C 99.96% | 0.04%	Bismuth	Bi^{214}	β and α γ—2.4	19.7 min.
Radium C′	Polonium	Po^{214}	α γ—.46	1.6×10^{-4} sec.
Radium C″ ↓	Thallium	Tl^{210}	β	1.32 min.
Radium D ↓	Lead	Pb^{210}	β γ—.80	19.4 yr.
Radium E 100% | 2×10^{-4}%	Bismuth	Bi^{210}	β and α	5.0 days
Radium F	Polonium	Po^{210}	α	138.4 days
Thallium-206 ↓	Thallium	Tl^{206}	β	4.20 min.
Radium G (End Product)	Lead	Pb^{206}	Stable	—

TABLE 3.1.—Decay of an Atom of Uranium.

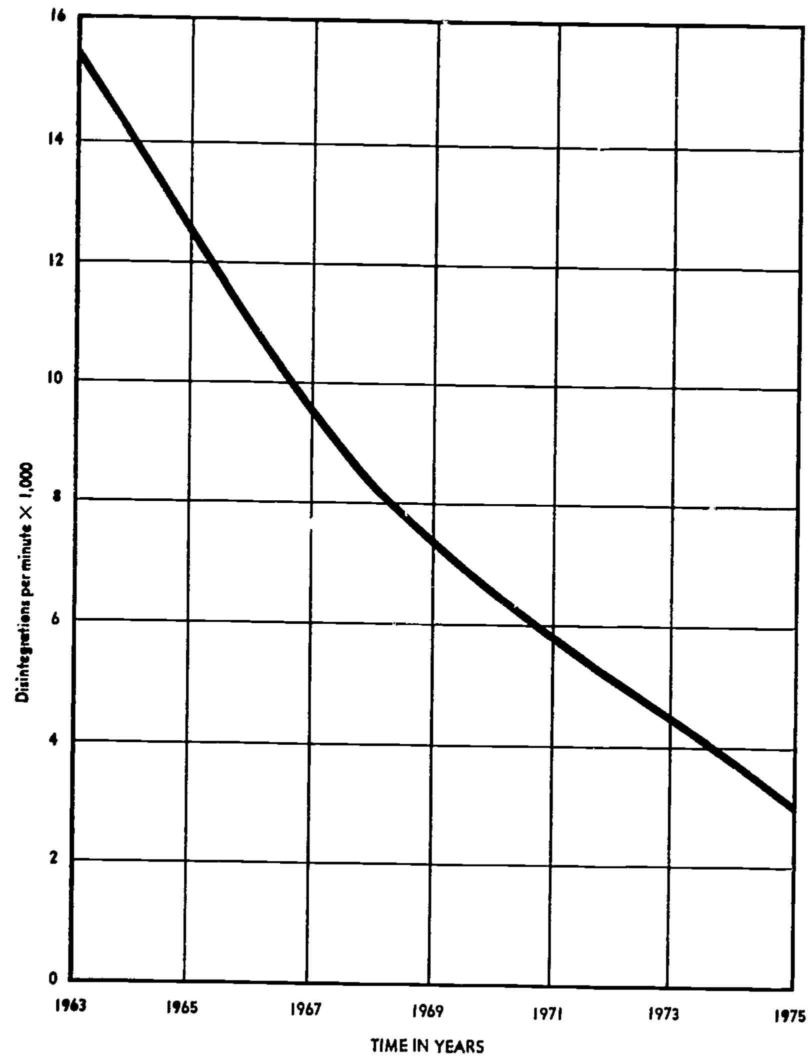


FIGURE 3.6.—Co-60 Decay Curve: Cartesian Coordinates.

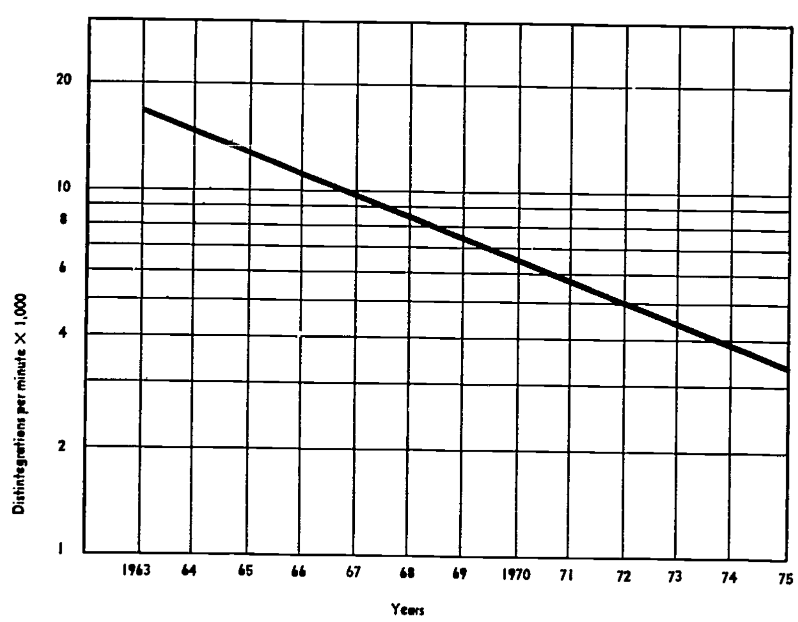


FIGURE 3.7.—Co-60 Decay Curve: Semi-log Coordinates.

3–10 Decay Schemes

As radioactive materials decay, they follow rather well defined schemes. Decay schemes are used to show the particles and gamma rays emitted as an unstable atom, decays to a stable atom. In such schemes, a horizontal line is drawn to indicate the energy level of a radioactive atom. Below this, another horizontal line is drawn to indicate ground level for the stable atom. Arrows sloping down and to the right indicate emission of a negative beta particle. Wavy lines drawn straight down indicate emission of a gamma photon. Decay schemes for Co–60 and Cs–137 are given in Figure 3.8. Notice that about 10 percent of the Co–60 atoms emit a beta particle and then emit a gamma photon of 1.33 Mev energy. About 90 percent of the Co–60 atoms emit a beta particle and then emit, in turn, a gamma photon of 1.17 Mev and one of 1.33 Mev. The final product is stable Ni–60.

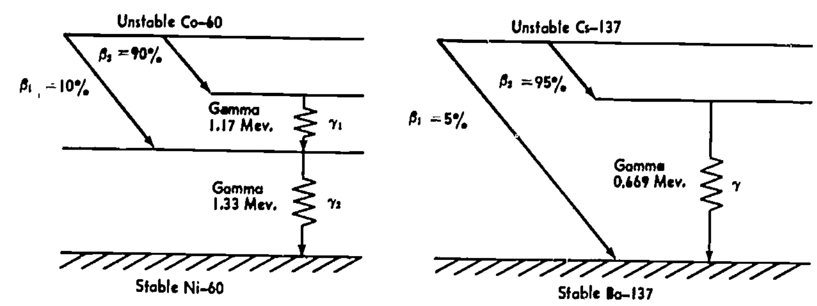


FIGURE 3.8.—Decay Schemes for Co–60 and Cs–137.

About 5 percent of the Cs–137 atoms emit a beta particle without emitting a gamma photon. The other 95 percent emit a beta particle before emitting a gamma photon of 0.669 Mev. Stable Ba–137 is the final product.

Chapter 4

Interaction of Radiation With Matter

4–1 Ionization and Ions

Atoms, molecules, and various subatomic particles which carry either a positive or negative electrical charge are called *ions*. Free electrons, not attached to any parent atom, are called *negative ions*. Other particles having negative electrical charges are also negative ions. The alpha particle, a helium nucleus, carries two positive charges and so is referred to as a *positive ion.*

Any action which disturbs the electrical balance of the atoms which make up matter is referred to as *ionization.* Radiation, either particles or electromagnetic, has the ability to ionize. A high-speed particle or a photon of energy which passes through matter will disrupt the atomic arrangement of the matter. For example, an alpha particle may strike an orbital electron in an atom and cause the electron to leave its orbit. The electron may attach itself to an atom. The first atom then has a positive charge and the latter atom a negative charge, and these are referred to as positive and negative ions. Also they may be called an *ion pair.*

The charge on a particle moving through matter also affects ionization. Thus the moving particle may attract or repel an orbital electron. Dislodged electrons may, themselves, cause other electrons to be driven from their orbits in what is called *secondary ionization.* This may continue, in fact, until the energy of the dislodged electron is below that necessary to drive other electrons from their orbits.

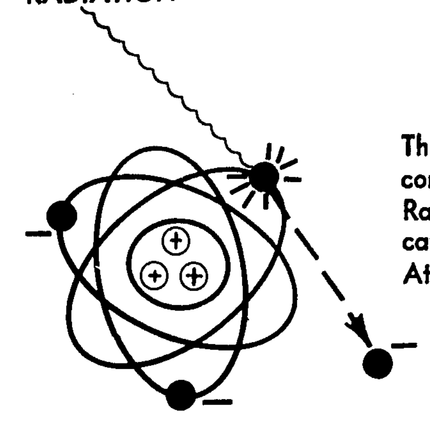


FIGURE 4.1.—Ionization.

The ionization process described here is the principal reason behind the various biological effects of radiation. The ionization of atoms which make up the cells of the body have very serious effects on these cells and body tissue. These are described in more detail later.

4–2 Ionization by Particles

In ionization by a particle there is an energy transfer from the particle to the orbital electrons of atoms. In this process the moving particle is slowed down. When the energy of the particle falls below that needed to ionize (dis-

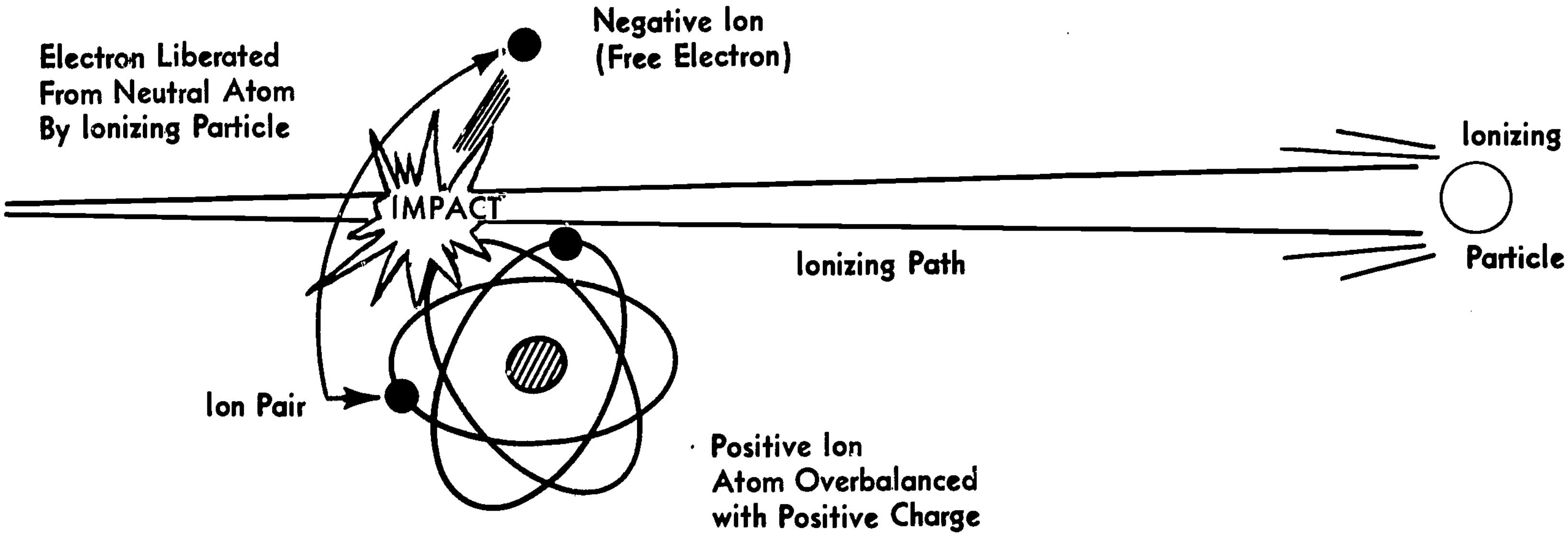


FIGURE 4.2.—Ionization by Particle Radiation.

lodge orbital electrons), the particle still may impart some energy to, or excite, electrons. The speed, mass, and charge of a particle all affect the transfer of energy to an electron. In turn the amount of energy received by the electron determines the amount of secondary ionization caused by the electron.

The number of ion pairs produced per unit length of a particle's track is called the *specific ionization* of the particle. This is generally stated as the number of ion pairs produced per centimeter of track in air. Differences in speed, mass, and charge greatly affect the specific ionization of particles. The total number of ion pairs produced by a particle, regardless of length of track, is called *total ionization.*

Alpha particles travel only about two inches in air and may be completely stopped by a sheet of paper. Thus high-energy alpha particles lose their energy rapidly. This means that they have a high specific ionization which ranges from 20,000 to 80,000 ion pairs per centimeter of air traveled. Alpha particles have energy ranging from about 4.0 to 10.6 million electron volts (Mev). The alpha particle is relatively large and slow moving. These factors cause it to have a high ionizing effect. Also, its positive charge causes it to dislodge nearby electrons due to coulombic attraction when there is no direct collision.

A beta particle travels much farther in matter than an alpha particle of the same energy. This is true because the beta particle is very small, moves at a very high rate of speed, and has less electrical charge than the alpha particle. Being light in weight, the beta particle is easily deflected so that distance from point of origin is not a good measure of distance traveled. Beta particles have a low specific ionization of 50 to 500 ion pairs per centimeter of air; they may travel several meters in air and attain speeds up to 99 percent of the speed of light. Beta particles have energy ranging from 0.025 to 3.15 Mev. Both the speed and the range of the beta particle are proportional to its energy.

The neutron having no charge does not ionize directly. A neutron passing through matter has a negligible effect upon orbital electrons in atoms of the matter. However, the neutron may strike the nucleus of an atom and cause reactions which will ionize. The nucleus may absorb the neutron and then emit particles which cause ionization. It may fission and the resulting fragments may emit ionizing particles, or the nucleus which is a charged particle itself may recoil and produce some ionization.[1]

4–3 Ionization by Electromagnetic Radiation

Gamma and X-rays are not particles and have no mass or weight. Therefore they do not produce ionization directly by collision as do alpha and beta particles. Since these rays or photons of energy travel at the speed of light, they do not lose their energy as readily as do the particles. Gamma and X-rays lose their energy to atoms by three processes known as *photoelectrical absorption, Compton scattering,* and *pair production.* When an atom absorbs energy by one of these three processes, it emits a charged particle, usually an electron. The emitted electron then may produce ionization in a manner similar to that of other ionizing particles. (Figure 4.3)

Gamma and X-rays are very penetrating, with a range depending upon their energy. It is not practical to measure the penetrating power of these rays in feet or meters. Instead, it is measured by the thickness of materials needed to reduce the rays to half their original intensity. The process by which the direction of incident radiation is changed is called *scattering.* This may occur in several ways. Scattering is of prime concern to the radiographer.

4–3.1 *Photoelectrical Absorption Process.* When gamma or X-ray photons of low energy penetrate matter, especially matter with a high atomic weight and many orbital electrons, the photon energy may be transferred to an orbital electron. Some energy will be used to dislodge the electron from its orbit and the remainder will be used to give the electron kinetic energy or a velocity. These are called photoelectrons, and the transfer of energy is called the photoelectric process. Only about 30 to 50 electron volts are needed to dislodge an electron, so the remainder of the energy of the photon gives the electron a high velocity. The moving electron then loses its energy, producing ion pairs through ionization as previously described. The photoelectric effect usually occurs with low energy gamma or X-photons of 0.1 Mev or less.

[1] RCA Service Company. *Atomic Radiation.* Camden, New Jersey, 1957. P. 9.

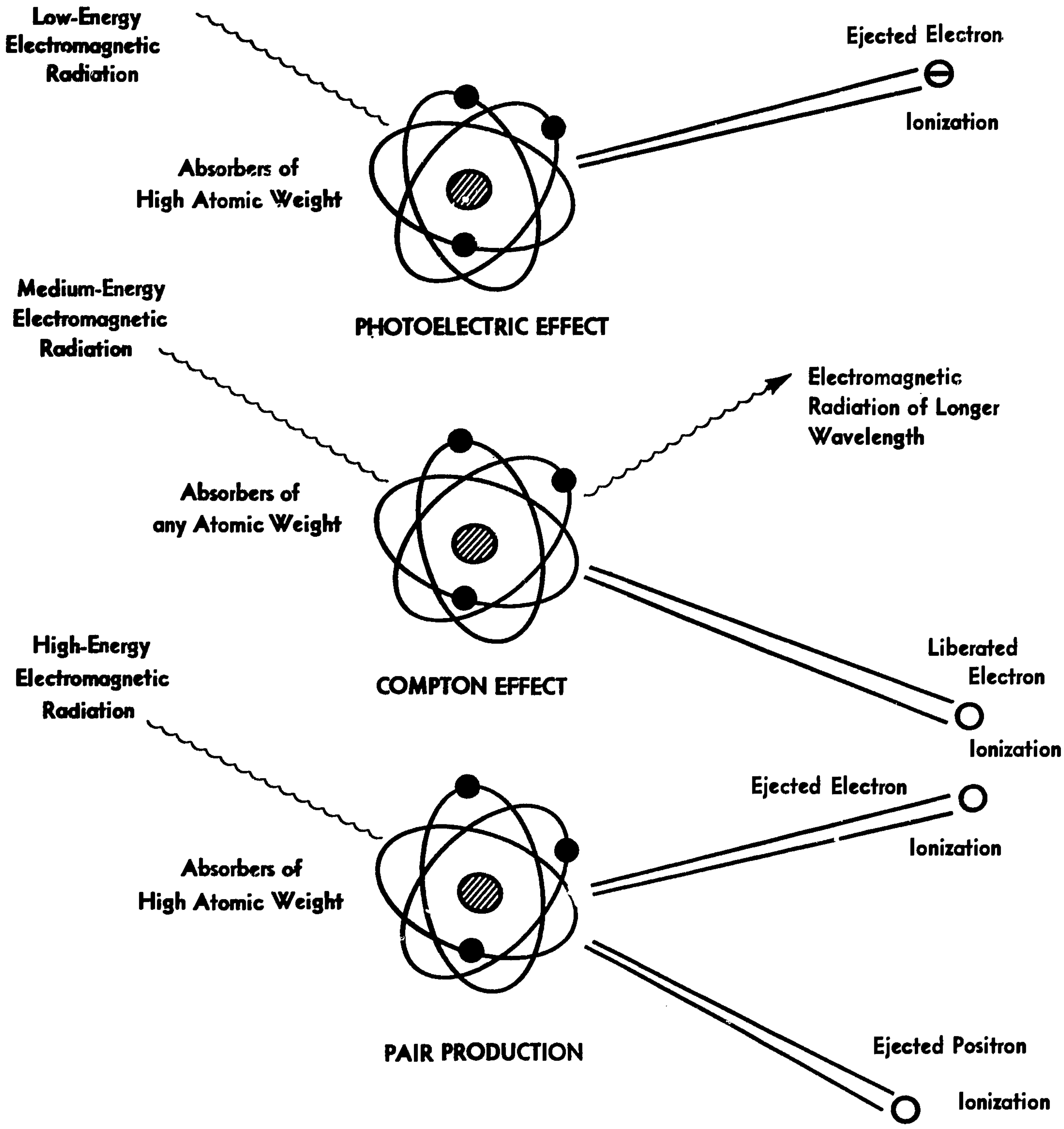


FIGURE 4.3.—Ionization by Electromagnetic Radiation.

4–3.2 *Compton Scattering.* When electromagnetic radiation consists of photons of about 0.1 to 1.0 Mev, Compton scattering occurs. In this process the photon does not lose all its energy to an orbital electron. Instead a part of the energy is transferred and a dislodged electron is emitted at an angle to the path of the original photon. Also a lower energy photon is scattered at an angle to the original photon path. This may be repeated until the original photon is completely absorbed by the previously described photoelectric effect.

4–3.3 *Pair Production.* Very high energy photons of 1.02 Mev or more cause ionization by a method called pair production. In this process a high energy photon approaches the nucleus of an atom and converts from energy into an electron-positron pair. A positron has the same mass as an electron but carries a positive charge. By Einstein's famous equation, $E = mc^2$, it has been found that the mass of one electron is equivalent to 0.51 Mev of energy. This explains the need for photons of 1.02 Mev so that the electron-positron pair can be formed. Any energy above 1.02 Mev causes the pair of particles to have kinetic energy or speed. The electron so formed may then cause ionization. The positron may cause ionization, but has an extremely short life. It combines with an electron and disappears with the emission of two gamma photons of 0.51 Mev each. These will act as other low energy gamma photons and may cause ionization by the photoelectric effect or by Compton scattering.

4–4 The Roentgen

An amount of radiation is not measured directly. Rather, the amount of ionization produced by passage of the radiation through some medium is used to measure radiation. The roentgen (r) is a measure of ionization in air due to passage of gamma or X-radiation. One roentgen, or one r, is that quantity of gamma or X-radiation that will produce 2.083×10^{9} ion pairs per cubic centimeter of air at standard temperature and pressure (0°C and 760 mm mercury). This is equivalent to 1.61×10^{12} ion pairs per gram of air and also is equal to one electrostatic unit (esu) of charge. In standard measures of energy one roentgen equals 83 ergs.

The roentgen is a rather large amount of radiation. Therefore, a subunit is used for convenience in measuring small amounts of radiation. This is the milliroentgen (mr), or one thousandth of a roentgen. Thus one roentgen equals 1000 milliroentgens.

The roentgen measures a definite amount of gamma or X-radiation in terms of their ionizing effect on air. Dosimeters measure a dose or number of roentgens or milliroentgens. Also useful is a dose rate concept. Ionizing rates are expressed in terms of roentgens per hour (r/hr) or milliroentgens per hour (mr/hr). Emission or dosage rate constants are useful to the radiographer when expressed as roentgens per hour per curie at a unit distance from the source. (See Table 4.1.) This term is called emissivity and has units—r/hr/c @ 1 ft. or mr/hr/mc @ 1 ft.

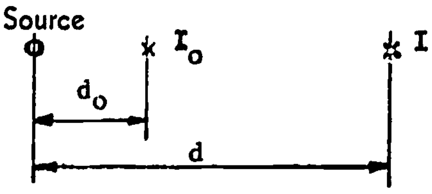
TABLE 4.1.—Dose Rate of Commonly Used Radioisotopes.

Radioisotope	Dose Rate r/hr/curie at 1 ft. Emissivity
Co–60	14.4
Cs–137	4.2
Ir–192	5.9
Ra–226	9.0

4–5 Radiation Attenuation

When a source of radiation is confined to that it may be considered a point source, the intensity of radiation is inversely proportional to the square of the distance from the source. The so-called "Inverse Square Law" is as follows:

$$\frac{I}{I_o} = \left(\frac{d_o}{d}\right)^2$$

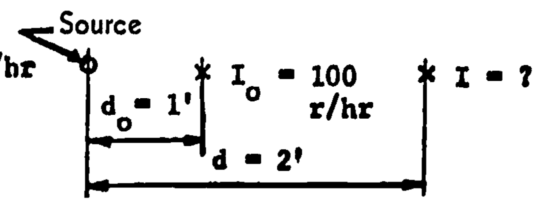


where: I = Radiation intensity at distance d
I_o = Initial radiation intensity at distance d_o
d_o = Initial distance from source
d = Distance at which intensity is I

It is possible to calculate the dosage rate at any point where emission constants are known.

Example: Suppose the emission of a source of radiation is 100 roentgens per hour at 1 foot. What is the dose rate at 2 feet? At 4 feet?

If I_o = 100 r/hr
d_o = 1 ft.
d = 2 ft.



Then $\frac{I}{100} = \left(\frac{1}{2}\right)^2$

$$I = 100 \times \left(\frac{1}{2}\right)^2 = 100 \times \frac{1}{4} = 25 \text{ r/hr}$$

If I_o = 100 r/hr
d_o = 1 ft.
d = 4 ft.

Then $\frac{I}{100} = \left(\frac{1}{4}\right)^2$

$$I = 100 \times \left(\frac{1}{4}\right)^2 = 100 \times \frac{1}{16} = 6.25 \text{ r/hr.}$$

Results of Calculations

Distance From Source Feet	Intensity mr/hr
1	4,800
2	1,200
3	533
4	300
5	192

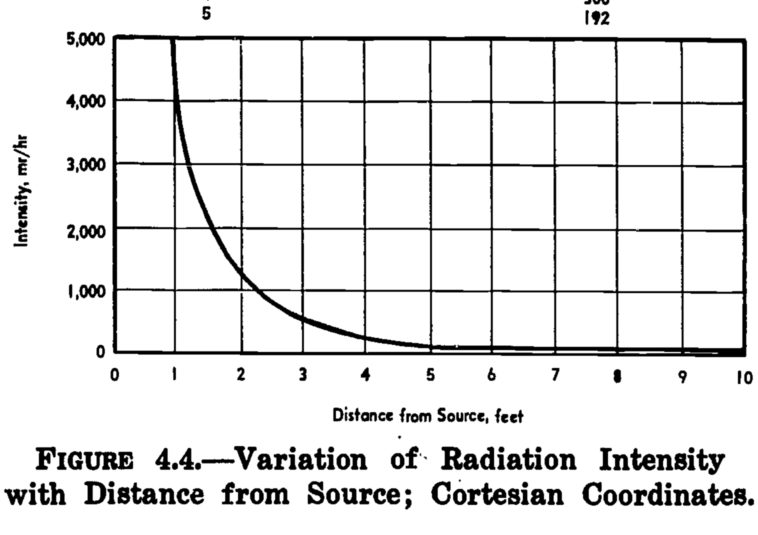


FIGURE 4.4.—Variation of Radiation Intensity with Distance from Source; Cartesian Coordinates.

Example: A 10-curie source of Co-60 is to be used at 10 feet from a group of workmen. What dose rate will they receive? What dose would they receive in 8 hours?

Note that the dosage rate for Co-60 is 14.4 r/hr/c at 1 ft.

If $I_o = 10 \times 14.4 = 144$ r/hr
$d_o = 1$ ft.
$d = 10$ ft.

Then $\frac{I}{144} = \left(\frac{1}{10}\right)^2$

$I = 144 \times \left(\frac{1}{10}\right)^2 = 144 \times \frac{1}{100} =$ 1.44 r/hr or 1440 mr/hr

In 8 hours the men would receive $8 \times$ 1440 mr/hr = 11,520 mr

Occasionally a known dosage rate is given and the distance from the source must be calculated.

Example: In the above example at what distance would the group of men receive only 2 mr/hr?

If $I = 2$ mr/hr
$I_o = 144$ r/hr = 144,000 mr/hr
$d_o = 1$ ft.

Then find distance d in the equation:

$$\frac{I}{I_o} = \left(\frac{d_o}{d}\right)^2$$

$$\frac{2}{144{,}000} = \frac{1}{d^2}$$

$$2\,d^2 = 144{,}000$$

$$d^2 = 72{,}000$$

$$d = \sqrt{72{,}000} = 268 \text{ ft.}$$

The variation in intensity with distance from source may be plotted (Figure 4.4).

Example: Suppose a radioisotope source has an emission of 6 mr/hr/mc at 1 foot. If an 800 mc source is used, determine the dosage rates at 2 ft., 3 ft., 4 ft., 5 ft.

$$\frac{I}{I_o} = \left(\frac{d_o}{d}\right)^2 \text{ or } I = I_o \times \left(\frac{d_o}{d}\right)^2$$

$$I = 6 \times 800 \times \left(\frac{1}{2}\right)^2 = 4800 \times \frac{1}{4}$$

= 1200 mr/hr (Figure 4.4)

4–6 Absorption of Radiation

Alpha rays are completely stopped by a few centimeters of air or a sheet or two of paper. Beta rays are stopped by a few meters of air or a few millimeters of lead. Gamma rays, however, can penetrate the most dense materials.

Gamma rays are diminished in number by any given absorber, but are not wholly stopped. If the number of monoenergetic gamma photons traversing an absorber is plotted against the thickness of the absorber, an exponential curve results. The intensity I of the gamma rays after passing through an absorber may be calculated by the formula:

$$I = I^o e^{-ut}$$

where

I_o = initial intensity of gamma rays
e = base of natural logarithms
^{u} = linear absorption coefficient of absorber for given gamma rays
t = thickness of absorber in centimeters

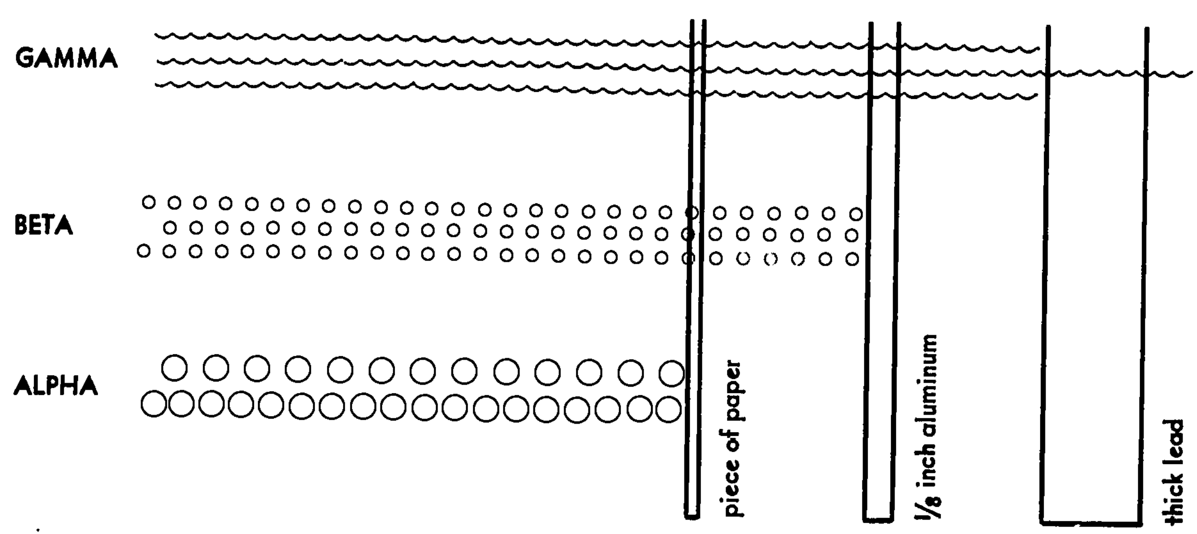


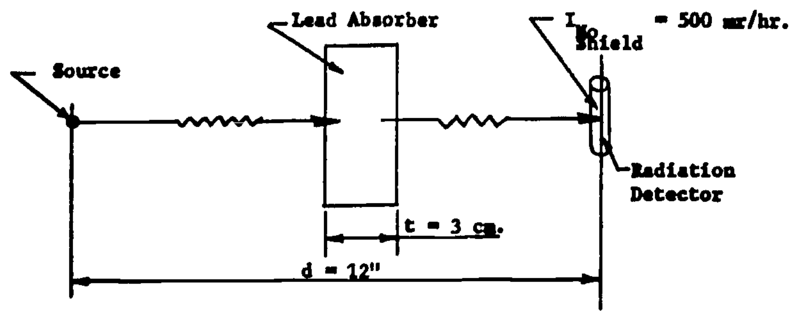
Figure 4.5.—Absorption of Radiation.

TABLE 4.2.—Linear Absorption Coefficients.

E (Mev)	*Absorption Coefficients per cm*			
	Pb	Fe	Al	H_2O
0.2	5.0	1.06	0.33	0.14
0.5	1.7	0.63	0.23	0.090
1.0	0.77	0.44	0.16	0.067
1.5	0.57	0.40	0.14	0.057
2.0	0.51	0.33	0.12	0.048
2.5	0.48	0.31	0.10	0.042
3.0	0.47	0.30	0.090	0.038
4.0	0.48	0.27	0.082	0.033
5.0	0.48	0.24	0.074	0.030

Example: An unshielded point source emitting 1 Mev gamma rays produces an emission of 500 mr/hr at 1 ft. What will be the dosage rate if there are interposed lead shields 1 cm. thick, 2 cm. thick, 3, 4, 5, and 10 cm. thick?

To compute intensity of radiation for the 3 cm. thickness of lead shielding, note that the linear absorption coefficient for lead at 1 Mev is 0.77 (Table 4.2).



$$I_3 = I^o e^{-ut}$$
$$= 500\ e^{-.77\times 3}$$
$$= 500\ e^{-2.31}$$
$$= 49.5 \text{ mr/hr at 1 ft.}$$

Results from calculations of radiation intensity passing through other thicknesses of lead are tabulated on Figure 4.6.

When the same data are plotted on semi-log paper, note that the exponential curve becomes a straight line. One advantage of using semi-log paper to plot such data is that only two points are needed to determine the straight line. (Figure 4.7)

4–7 Half-value Layers

There is little use in trying to compute the amount of shielding necessary to stop gamma or X-radiation, since a point is never reached when all such radiation is stopped. A convenient measure is that amount of shielding which will stop half of the radiation of a given intensity. This measure is called the ***half-value layer.*** The half-value layer of an absorber is related to the linear absorption coefficient by the following equation:

$$HVL = \frac{0.693}{\mu}$$

where

HVL = half-value layer (centimeters)

μ = linear absorption coefficient (in reciprocal centimeters)

Example: Suppose there is a 1.0 Mev source of gamma radiation. The linear absorption coefficient of lead for 1.0 Mev radiation is 0.77. What is the half-value layer of lead?

$$HVL = \frac{0.693}{0.77} = 0.90 \text{ cm}$$

Therefore, nine-tenths of a centimeter of lead will reduce gamma radiation of 1.0 Mev energy to one-half its intensity.

Example: A 10–curie source of Co–60 is to be used at 10 feet from a group of workmen. How much lead shielding would be needed to reduce the dose rate to 2 mr/hr? (Figure 4.8)

Results of Calculations

Lead Shield Thickness Centimeters	Intensity mr/hr
1	225
2	107.2
3	49.5
4	23
5	10.6
10	0.227

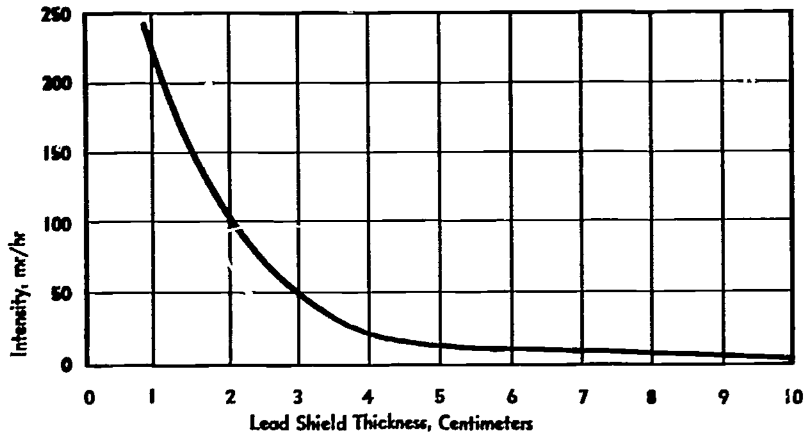
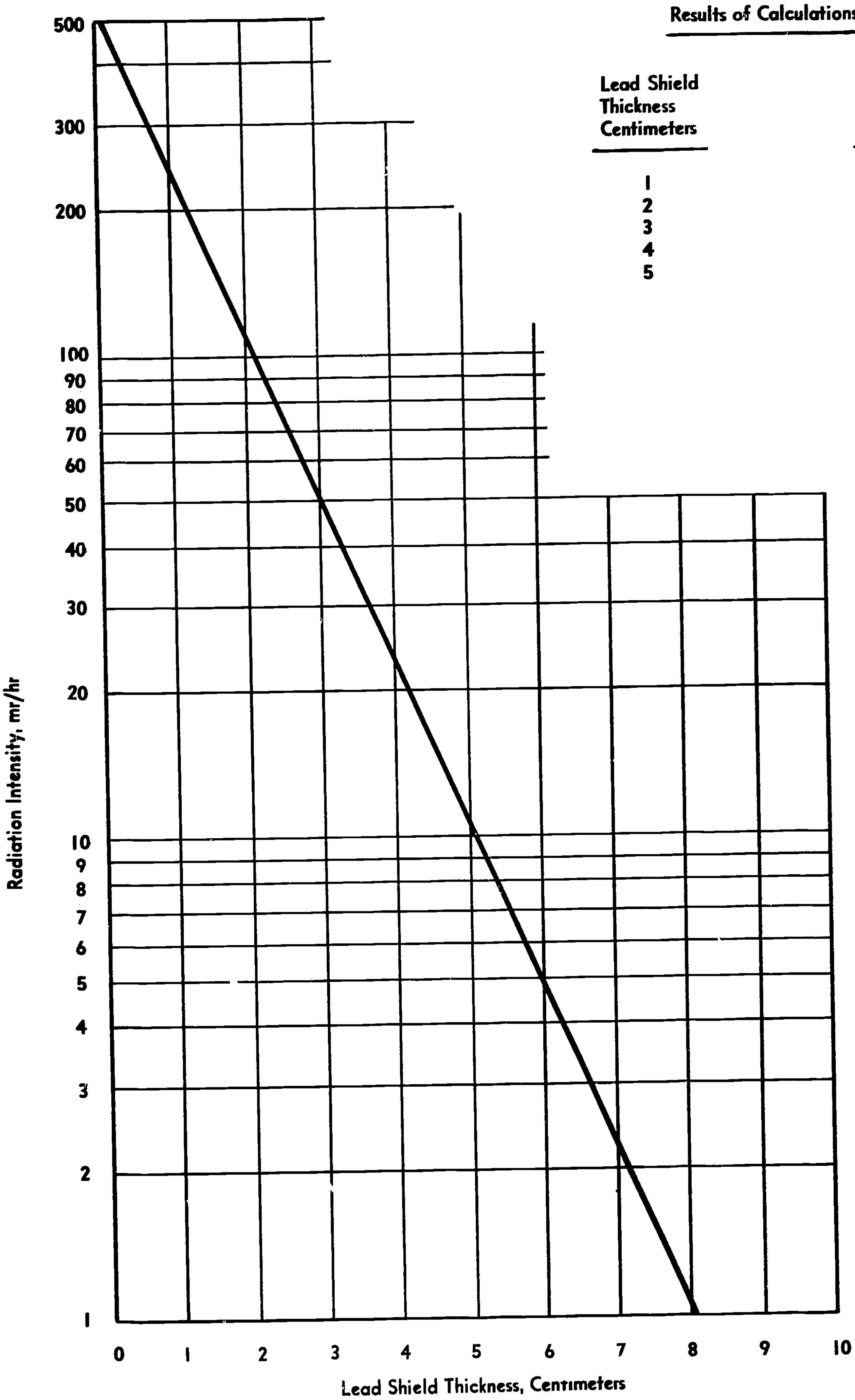


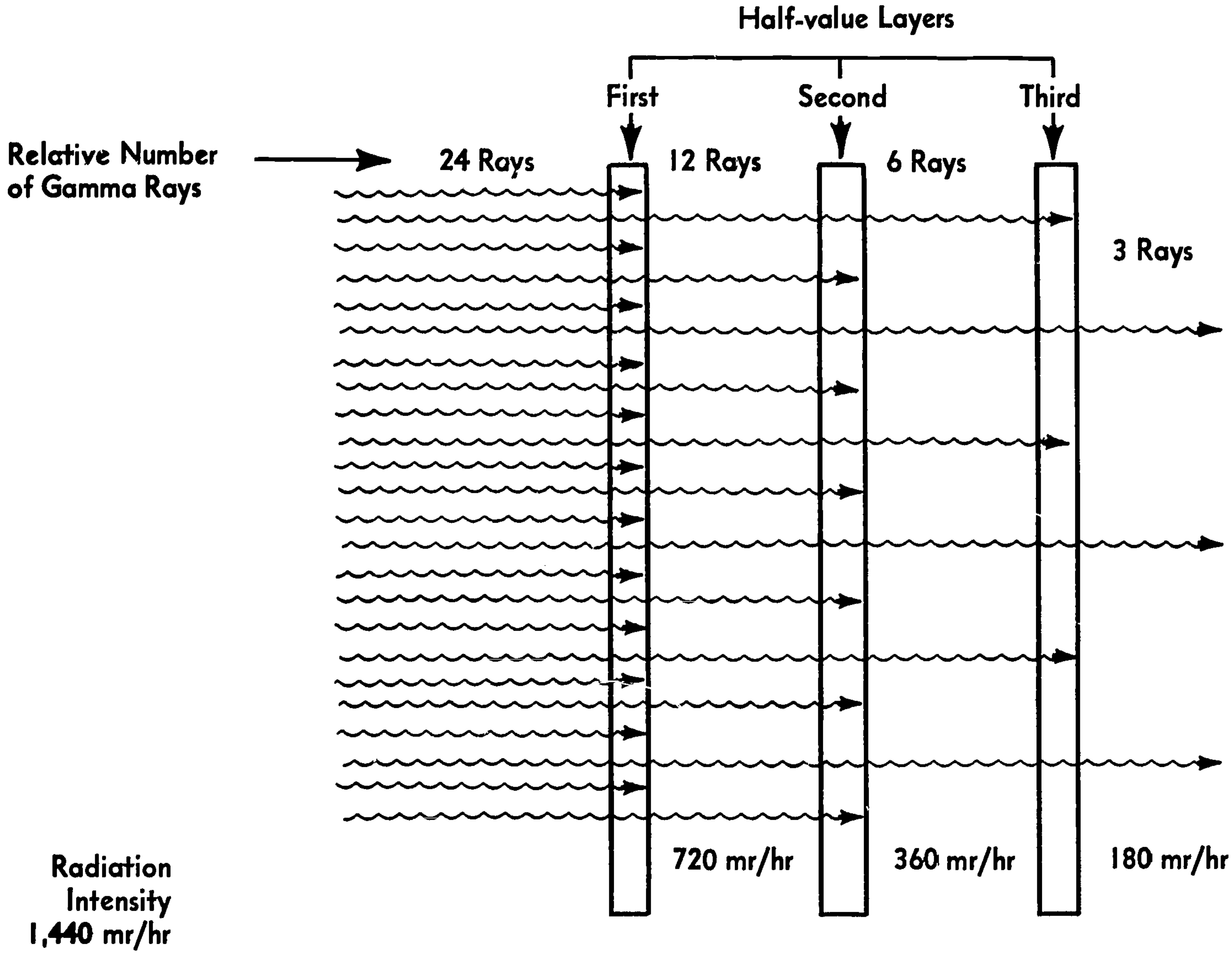
FIGURE 4.6.—Variation of Radiation Intensity with Lead Shielding; Cartesian Coordinates.



Results of Calculations

Lead Shield Thickness Centimeters	Intensity mr/hr
1	225
2	107.2
3	49.5
4	23
5	10.6

FIGURE 4.7.—Variation of Radiation Intensity with Lead Shielding; Semi-log Coordinates.



Approximate Half-value Layers for Shielding Radiography Sources (including build-up)

	Half-value layer thickness* in inches		
Radiography source	Lead ½	Iron ½	Concrete (147 lbs./cu. ft.) ½
Co–60	0.49	0.87	2.7
Ra–226	0.56	0.91	2.9
Cs–137	0.25	0.68	2.1
Ir–192	0.19		1.9

*The thicknesses for half-value layers provide shielding protection from the scattered radiation resulting from deflection of the primary gamma rays within the shield as well as protection for primary radiation from the source.

FIGURE 4.8.—Half-value Layers.

Since the energy of emission of Co–60 is approximately 1 Mev, the half-value thickness of lead would be .90 centimeters. From a previous example it was found that the dosage rate for the workmen was 1440 mr/hr.

1 HVL reduces 1440 mr/hr to 720 mr/hr
2 HVL reduce 1440 mr/hr to 360 mr/hr
3 HVL reduce 1440 mr/hr to 180 mr/hr
4 HVL reduce 1440 mr/hr to 90 mr/hr
5 HVL reduce 1440 mr/hr to 45 mr/hr
6 HVL reduce 1440 mr/hr to 22 mr/hr
7 HVL reduce 1440 mr/hr to 11 mr/hr
8 HVL reduce 1440 mr/hr to 5.5 mr/hr
9 HVL reduce 1440 mr/hr to 2.75 mr/hr
10 HVL reduce 1440 mr/hr to 1.375 mr/hr

Ten half-value layers of lead shielding would be required to reduce the dose rate to a value less than 2 mr/hr.

This would result in a shield thickness: $10 \times .90$ centimeters = 9 centimeters.

Since 1 centimeter = .4 inch, then the lead shielding would need to have a thickness of

$9 \times .4 = 3.6$ inches (not including buildup).

As radiation passes through materials there will be some radiation "scattered." The result is that more radiation will pass through an absorber than is indicated by the absorption equation. This increase has been named "buildup." It depends upon the radiation energy (Mev) and the atomic number (Z no.) of the absorber. Calculations involving buildup factors may become quite complicated. For this reason, the calculations acceptable for radiography purposes can be made using half-value layers and reduction factors.

If buildup had been given consideration in the preceding example, the results would have been:

Example: One lead HVL for Co–60 radiation is 0.49″ (refer to Figure 4.8).
$10 \text{ HVL} \times 0.49'' = 4.9''$ lead required

This clearly indicates that buildup is an important factor in shielding design.

Materials having a high atomic number absorb more gamma radiation than materials having a low atomic number. Some frequently used shielding materials are lead, iron, concrete, and water. (Figure 4.9)

4–8 Reduction Factors

The concept of a *reduction factor* is useful in computing the amount of shielding needed. The reduction factor is the dose rate of gamma radiation reaching a point at some distance from a source with no shield divided by the dose rate reaching the same point with some shield interposed. This reduction factor depends upon the radiation energy (Mev) and the shield's atomic number, thickness, and density.

$$\text{Reduction Factor} = \frac{\text{Dose Rate Without Shield}}{\text{Dose Rate With Shield}}$$

Figures 4.10, 4.11, and 4.12 show the reduction factor for gamma radiation from Co–60, Ra–226, Cs–137, and Ir–192 plotted against shield thickness for lead, iron, and concrete. The data on these graphs are for broadbeam radiation since it includes absorption of scattered radiation caused by reflected primary gamma radiation, i.e., buildup is included.

Example: Suppose a Co–60 source of radiation has an intensity of 2,000 mr/hr at a distance of 10 feet. Workmen need to be at that distance from the source but should receive only 4 mr/hr. How much lead shielding should be used? Iron? Concrete?

$$\text{Reduction Factor} = \frac{2{,}000}{4} = 500$$

Lead—4.6 inches
Iron—7.8 inches
Concrete—24.5 inches

It is very important for the radiographer to remember that the interaction of radiation with matter depends upon (1) the gamma ray energy (Mev) and (2) the atomic number (somewhat related to density). By referring to Figure 4.8, it is possible to consider the half-value layer thickness variations with no change in gamma ray energy. For example, observe that:

(1) The atomic number and density decrease while reading across the table columns from lead to iron to concrete.
(2) For a selected radioisotope, e.g., Cs–137, the half-value layer thickness increases as one reads across the table —0.25" for lead to 0.68" for iron to 2.1" for concrete.

This is acceptable for calculations using heavy shield materials for high energy gamma rays. Similar conclusions can be drawn from data in Figures 4.10, 4.11, and 4.12.

Example: To demonstrate the thickness variation of a selected shielding material when using energies from several radioisotopes, determine the lead thickness at a reduction factor of

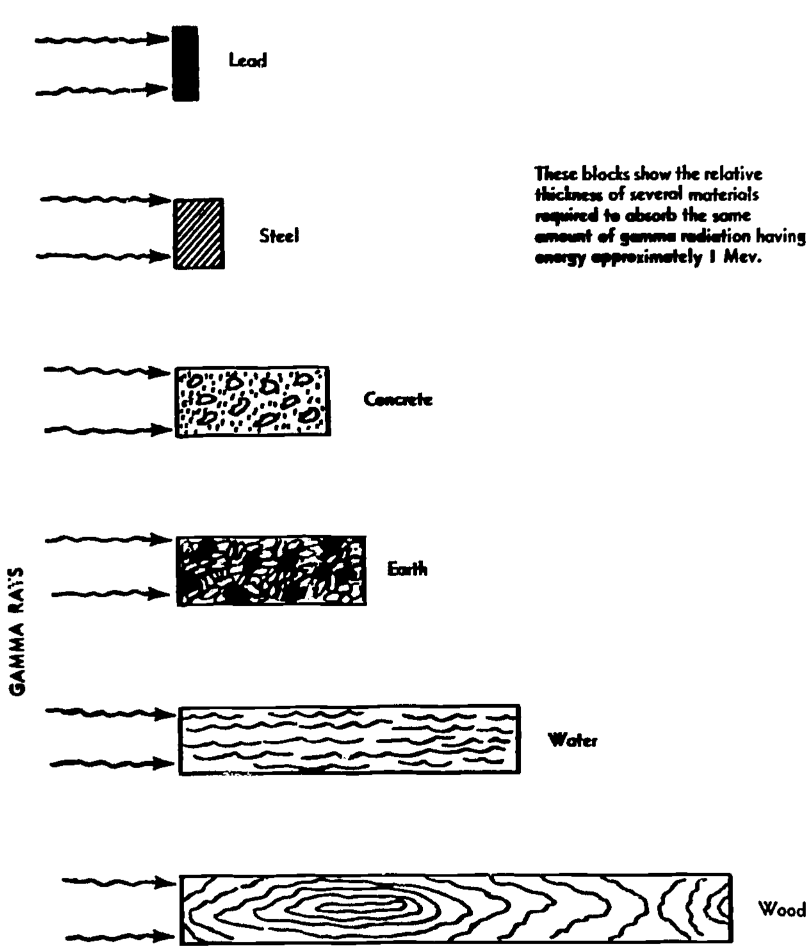


Figure 4.9.—Relative Efficiency of Shielding Materials.

1,000 to shield Ir–192, Cs–137, and Co–60.

Radioisotope	*Lead Thickness*
Ir–192	1.9
Cs–137	2.6
Co–60	4.8

Example: A radiographer plans to make a radiograph in a location where it is necessary for people to work periodically as close as 10 ft. to a 500 mc source of Co–60. He plans to reduce the dose rate to 6 mr/hr by placing a portable iron shield between the radiographic setup and the work area. What thickness shield would be needed to attenuate the gamma radiation to the required level?

Find the exposure rate at 10 feet from the 500 mc source of Co–60. One curie of Co–60 has an exposure rate of 14,400 mr/hr at 1 foot. Therefore, 500 mc would have an exposure rate one-half this amount, or 7,200 mr/hr at 1 ft. From the equation:

$$\frac{I}{I^o} = \frac{d_o^2}{d^2}$$

the exposure rate at 10 ft. may be found

$$\begin{aligned} I\ (10\ \text{ft}) &= I_o \times \frac{d_o^2}{d^2} \\ &= 7{,}200 \times \frac{(1\ \text{ft.})^2}{(10\ \text{ft.})^2} \\ &= 7{,}200 \times \frac{1}{100} \\ &= 72\ \text{mr/hr} \end{aligned}$$

The 72 mr/hr dose rate must be reduced by the iron shielding to 6 mr/hr.

$$\begin{aligned} \text{Reduction Factor} &= \frac{72\ \text{mr/hr}}{6\ \text{mr/hr}} \\ &= 12 \end{aligned}$$

A reduction factor of 12 for Co–60 in iron from Figure 4.11 indicates that an iron shield 3.5 inches thick is necessary to reduce the radiation to 6 mr/hr.

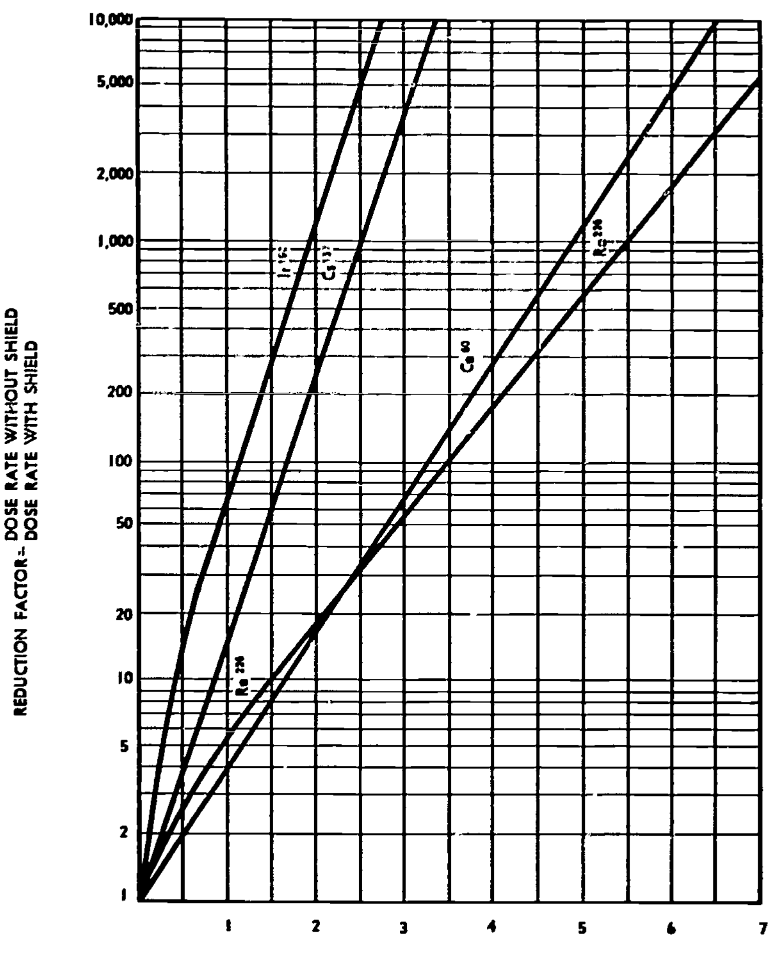


FIGURE 4.10.—Broadbeam Shielding for Absorption of Gamma Rays in Lead.

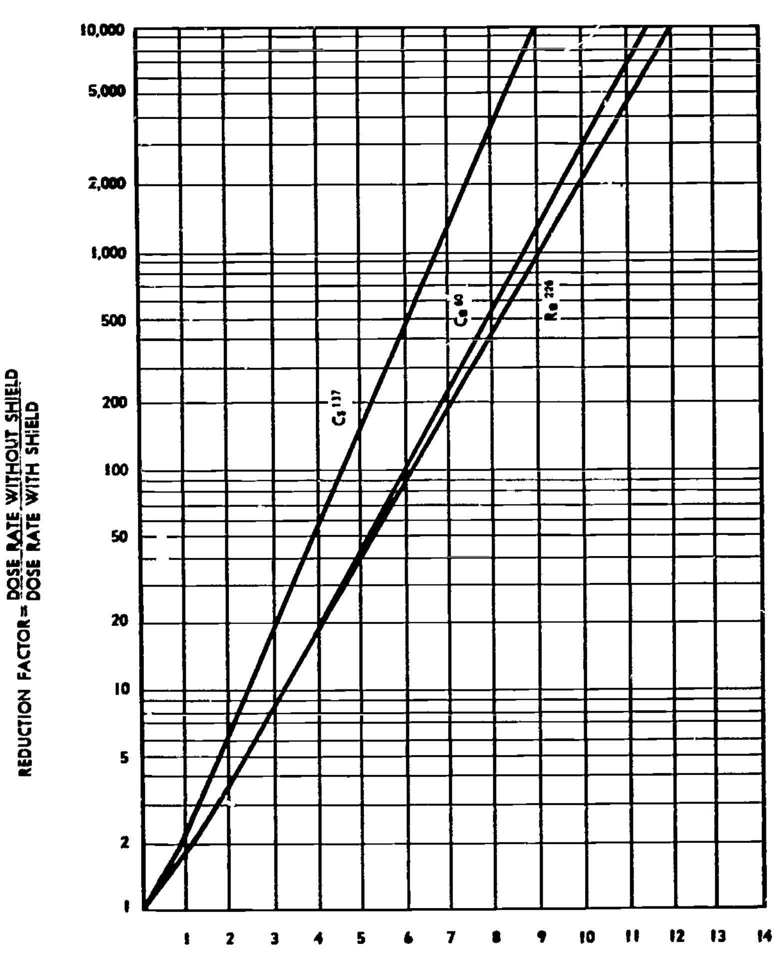


FIGURE 4.11.—Broadbeam Shielding for Absorption of Gamma Rays in Iron.

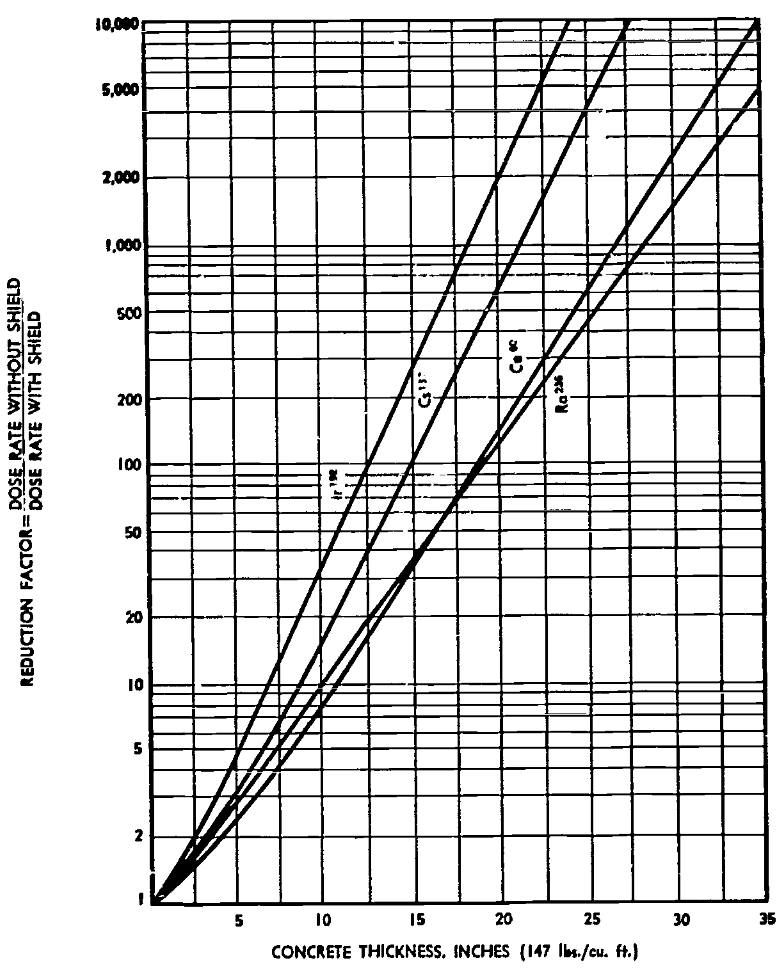


FIGURE 4.12.—Broadbeam Shielding for Absorption of Gamma Rays in Concrete.

4–9 Principles of Radiation Safety

All industrial radiography operations require the use of radiation sources having high energy, kev or Mev, and sources having high roentgen emission rates. Unless adequate radiation safety precautions are well understood, organized, and utilized, there can be overexposures to personnel.

The information presented in this chapter provides the basic concepts for using high intensity sealed gamma and X-ray sources. Only external radiation hazards need to be considered in radiography since, except for leaking sources, there is no way for the radioactive material to be taken into the human body. When properly trained persons use radiography sources there is no more reason to be afraid of the radiation hazard than to be overconcerned with safety problems when working with electrical systems or toxic chemicals.

Three principles must be applied for controlling body exposure to sources. These are (1) *time*, (2) *distance*, and (3) *shielding*.

All radiography installations and techniques should be designed using these principles. All

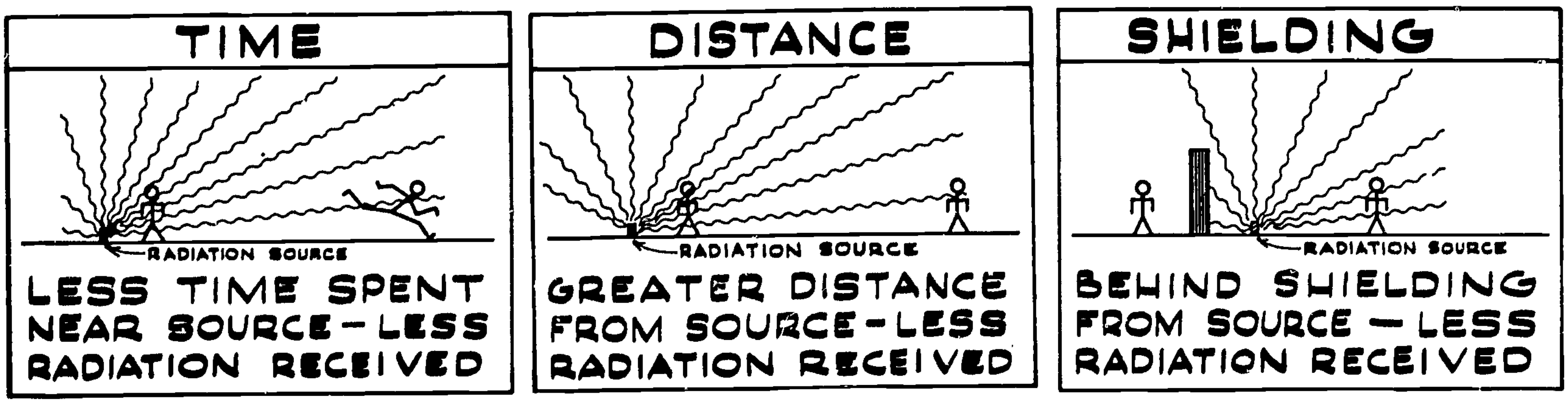


FIGURE 4.13.—Principles of Radiation Safety.

radiography operations should be frequently inspected to assure that the radiographer maintains the planned conditions associated with the source exposures.

4–9.1 *Personnel Exposure Time.* Personal dosage received depends directly upon the time a person remains in the radiation field. He would receive only 3 mr in 2 minutes at a given point where he would receive 15 mr if he had remained 10 minutes. Limiting the working time in a radiation field requires using suitable instruments, paragraph 5–5, for detecting and measuring the radiation intensity and applying the equation:

$$\text{Allowable working time in hr/week} = \frac{\text{permissible exposure in mr/wk}}{\text{exposure rate in mr/hr}}$$

Table 13.1 in Chapter 13 lists personnel exposure limits. A radiographer may use the more convenient limit that 100 mr/week should be his "radiation protection guide." The work should be organized in such a way that no radiation workers could receive more than 100 mr/week.

4–9.2 *Working Distances.* Lower personnel exposures will be received at longer distances from radiation sources. The inverse square law, paragraph 4–5, and the examples, give information and methods that permit the radiographer to calculate the radiation intensities at various distances from a source. Survey meters should be frequently used to verify the calculations. Table 4.3 tabulates useful data that verify the importance of working at various distances from gamma emitting sources.

4–9.3 *Radiation Shielding.* In the event that working time is too long, and operating conditions prevent sufficiently long exposure distances, the radiographer may place shielding material in the radiation beam to protect personnel. Shields will not stop all of the radiation, paragraph 4–6. Adequate shielding will attenuate the radiation to a value that will permit radiography operations without excessive or harmful personnel exposures. Using the absorption equation, page 29, half-value layers, or reduction factor methods for shielding calculations, will be adequate for radiographers.

In many industrial situations there will be requirements to use high intensity sources to produce the desired number of radiographs each week.

Limited space will be available. In these cases, shielding will be necessary. Suitable protection will require the radiographer to use *time, distance,* and *shielding.* This can best be illustrated with an example.

Radioisotope	r/hr at various distances in ft. from source					
	1	2	4	8	16	32
Co–60	14.4	3.6	0.9	0.23	0.06	0.014
Ra–226	9.0	2.3	0.6	0.14	0.035	0.009
Ir–192	5.9	1.5	0.4	0.09	0.023	0.006
Cs–137	4.2	1.1	0.26	0.07	0.016	0.004

TABLE 4.3.—Dose Rate of Unshielded Gamma Radiation at Distances from One-curie Sources Commonly Used in Radiography.

Example: A foundry produces castings which require 50 radiographs each week. A 30–curie cobalt–60 source is needed to make each exposure in 6 minutes. Only a small shop floor area is available. This requires that the radiographer work within 10 ft. from the exposed source. Determine the concrete shield thickness that must be provided to prevent the radiation workers from receiving more than 100 mr/week.

Step 1: Determine the length of time the source will be exposed:

50 exposures × 6 minutes exposure = 300 minutes

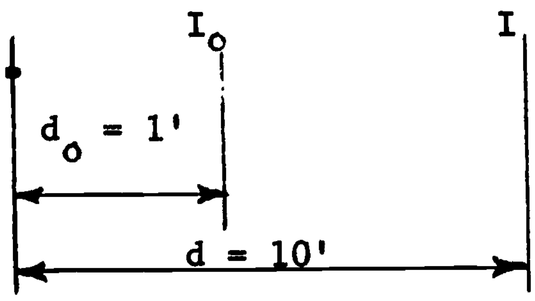
$$\frac{300 \text{ minutes}}{60 \text{ min/hr.}} = 5 \text{ hours}$$

Step 2: Calculate the personnel exposure rate in mr/hr which will allow radiographs to be made, but without the radiographer receiving more than 100 mr during the week:

$$\frac{100 \text{ mr/week}}{5 \text{ hours/week}}$$

= 20 mr/hr maximum exposure rate allowable for this situation

Step 3: Determine the gamma field intensity at 10 ft. from the 30–curie cobalt–60 source:



$$I = I_o\left(\frac{d_o}{d}\right)^2$$

$$I = 30 \times 14{,}400\left(\frac{1}{10}\right)^2 = 4{,}320$$ mr/hr at 10′ from the source with no shield

Step 4: Using the half-value layer concept, determine the concrete shield thickness that uce the radiation intensity below the allowable 20 mr/hr:

1 HVL reduces 4,320 to 2,160 mr/hr
2 HVL reduce 2,160 to 1,080 mr/hr
3 HVL reduce 1,080 to 540 mr/hr
4 HVL reduce 540 to 270 mr/hr
5 HVL reduce 270 to 135 mr/hr
6 HVL reduce 135 to 67.8 mr/hr
7 HVL reduce 67.8 to 33.9 mr/hr
8 HVL reduce 33.9 to 16.9 mr/hr

The HVL for concrete and cobalt–60 is 2 7″

8 × 2.7 = 21.6″ concrete which weighs 147 lbs/cu. ft.

For comparison, determine the shield thickness using the reduction factor:

$$\text{Reduction Factor} = \frac{\text{Dose Rate Without Shield}}{\text{Dose Rate With Shield}} = \frac{4{,}320 \text{ mr/hr Without Shield}}{20 \text{ mr/hr With Shield}} = 216$$

Using Figure 4.12, enter the curve sheet at R.F. = 216 in the left margin. Follow a horizontal line across to the cobalt–60 curve. From that intersection, move down and read the shield thickness at the bottom of the page. This value is 21.5″ concrete.

The results from the HVL method and the reduction factor method are comparable.

Chapter 5

Radiation Detection and Measurement

5–1 Radiation Detection and Measurement

Man cannot detect with his senses radiation coming from radioactive materials. The body may be penetrated by high intensity radiation and feel no pain, even though it may be severely injured by the radiation. This is similar to the reaction of man to ultraviolet and radio waves. A person may be exposed to the ultraviolet rays in sunlight and feel pain from overexposure several hours later. Likewise, a person receiving an overexposure of radiation may not be aware of it until some time later when radiation sickness develops. Man must, therefore, depend on some kind of instrument to detect nuclear radiation that may be of danger to him.

The term "detection" usually includes only a determination of the presence of radiation, whereas "measurement" includes both the detection and some measure of the amount of radiation present. Radiation detection or measurement instruments detect the interaction of radiation with some type of matter. Some instruments are based on the ionization produced in the instrument by the passage of the radiation; in other instruments the excitation of materials is used to detect radiation. These are the scintillation-type monitoring instruments. Chemical and photographic detection techniques are also used.

5–2 Radiation Measurement

Radiation measuring instruments usually provide a measurement of dose or of dose rate. The first measurement refers to the accumulated exposure dose of radiation over a period of time. The second measurement refers to an immediate measure of dose rate or radiation intensity.

The unit of radiation exposure is the roentgen, which is based on the effect gamma or X-radiation has as it passes through air. This is a rather large unit for measuring occupational exposures, so the milliroentgen is frequently used for measuring small doses of exposure (1 roentgen = 1,000 milliroentgens).

Instruments which measure total dose exposure are called *dosimeters.* If a workman is to be in an area where he is exposed to radiation, he may want to know his total dose exposure. A dosimeter would be used to tell him his total dosage upon completion of his work in that area. Examples of dosimeters include the Lauritsen electroscope, the pocket dosimeter, the R–meter, and film badges.

Instruments used to measure dose-rate exposure or radiation intensity are called *survey meters.* A workman may know that an area has radiation, but may not know the intensity of the radiation. A survey meter will tell him the dose rate and hence whether it is safe to enter the area or not. Examples of dose-rate instruments include the Geiger counter and the ionization chamber.

Except for photographic film techniques and a few special methods, all radiation-detecting devices are based upon the ionization produced in a gas by the radiation. When a high-speed particle or a photon enters a gas, it may act on an atom or molecule with a force large enough to remove an electron and form an ion pair of charged particles. Each charged particle is accompanied by an electric field that moves with the particle.

5–3 Dosimeters

Several types of total dose exposure instruments are of interest to the person working where radiation is present.

5–3.1 *Lauritsen Electroscope.* An ionization chamber is a closed vessel used for collecting the ions formed by high-energy radiation. A chamber usually consists of a cylindrical conducting shell with an insulated central electrode. The electrode consists of two parts, one fixed and one movable. The two parts are electrically connected, and both receive the same charge. Consequently there is a force of repulsion between them, and the movable part is deflected a distance proportional to the charge on the electrode. As rays enter the ionization chamber and create ions in the gas there, the ions with a charge opposite that of the electrode travel toward it. When they reach it, they give up their charge and neutralize an amount of charge on the electrode.

The amount of charge carried by any single particle is minute and has little visible effect on the electrode. As the radiation process continues, the electrode is discharged appreciably, and the change in position of its movable part can be interpreted in terms of roentgens. This allows determination of the total dose of radiation absorbed by the electroscope (and the person carrying the electroscope). One of the most useful instruments of this type is the Lauritsen Electroscope (Figure 5.1). In this instrument, the electrode consists of a metal wire and a quartz fiber. The wire, bent into the form of an L, is mounted on the electroscope case through an insulating bead of quartz or amber. Cemented to one end of the L is the quartz fiber, made conductive by a thin metal coating. To make the position of this fiber visible through the eye piece of the instrument, a second quartz fiber is fused to its free end, forming a T. Light comes in through a small window in one end of the electroscope so that the head of the T and a transparent scale can be seen through the eye piece of the microscope at the other end.

To prepare the electroscope for the measurement of radiation, the L-shaped wire and the conducting fiber are charged from a battery. Both the L and the fiber then have the same polarity of charge, and the mutual repulsion between them causes the quartz fiber to deflect from the side of the L. The voltage to which they are charged is of sufficient magnitude to make the head of the fiber T coincide with the zero mark on the scale when viewed through the eye piece.

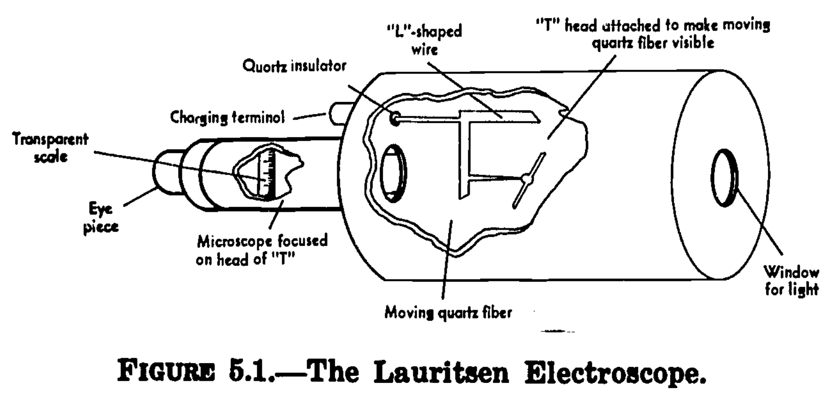


FIGURE 5.1.—The Lauritsen Electroscope.

When the instrument is brought into an area where there is radiation, ions are formed inside the case as the result of the radiation. Those ions which have a charge opposite that of the electrode travel to it and give up their charge on the wire and the fiber. This reduces the repulsion between them, and as a result the fiber returns toward its uncharged position, the distance of return depending on the amount of radiation and consequent ionization.

After the electroscope has been in the area to be surveyed for the desired length of time, the observer, looking through the eye piece and noting the position of the quartz fiber T with respect to a transparent scale calibrated in roentgens, can determine the quantity of radiation received during the period of observation.

5–3.2 *The Pocket Dosimeter and Pocket Chamber.* Another useful quartz fiber instrument is the pencil-type, or pocket, dosimeter (Figure 5.2) which is essentially a Lauritsen electroscope modified so that it is about the size of a large fountain pen. The electrode in the dosimeter consists of two quartz fibers, one fixed and one movable, but each bent into a U shape. The two fibers are fused together at the ends of the U, and a microscope is focused on the opposite end of the movable fiber. As with the Lauritsen electroscope, the dosimeter is charged from a separate source with a high enough voltage to deflect the movable fiber to

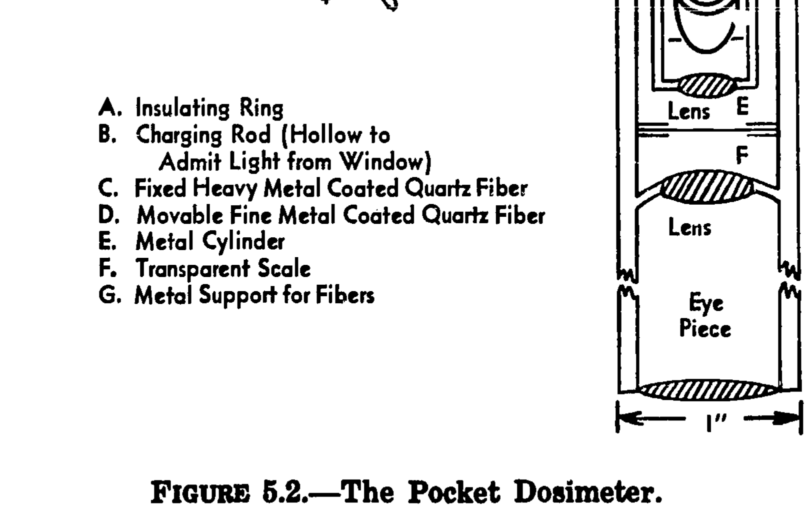


FIGURE 5.2.—The Pocket Dosimeter.

the zero point on the scale. The presence of radiation then produces ionization, neutralizes the charge, and allows the movable fiber to return toward the fixed fiber, a distance proportional to the quantity of radiation absorbed. Dosimeters can be made sufficiently rugged to withstand the shocks of normal human activity, are small enough to be worn comfortably, and are useful for measuring total exposure. Their sensitivity can be made such that 100 mr will produce about one-half full scale deflection.

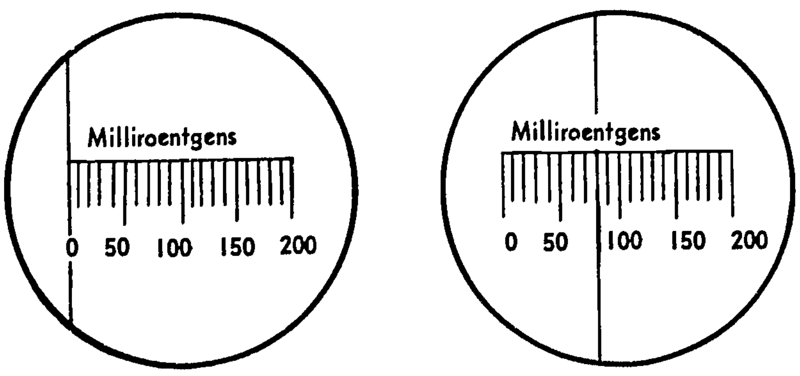


FIGURE 5.3.—Dosimeter Scales.

To prepare a pocket dosimeter for measuring radiation, it is charged to about 150 volts to bring the image of the quartz fiber to zero on the scale (Figure 5.3). A pocket dosimeter is charged by an external source of voltage. The ionization chamber is held at ground potential and the metal frame and quartz fiber are charged to the potential of the charger. The fiber and metal frame repel each other since they are at the same potential. The position of the fiber then varies with the voltage difference between the ionization chamber and the fiber. The variance is linear over the range covered by the scale. Dosimeters with scales such as those shown are called direct-reading dosimeters. Other types require a reading device and are called pocket chambers (Figure 5.4).

5–3.3 *The R-meter.* The R-meter is an ionization type of instrument which is made in a variety of styles for radiation detection under differing circumstances. In general, this instrument is composed of two main components, one, a thimble chamber or roentgen meter, and the other, an instrument for charging and measuring the exposure to which the thimble chamber was subjected. A roentgen meter is a special form of electrical condenser. The negative plate is the barrel of the meter. The positive plate of the condenser is the electrode which is mounted rigidly in a coaxial relationship with the barrel and insulated from it. Space between the electrode and the inner surface of the barrel is filled with air. When X- or gamma radiation passes through the chamber, the air is ionized in an amount directly proportional to the quantity of the radiation. Free electrons are collected by the positively charged electrode. Positive ions travel to the negatively charged wall of the chamber. This action discharges the chamber in direct proportion to the quantity of radiation passing through it.

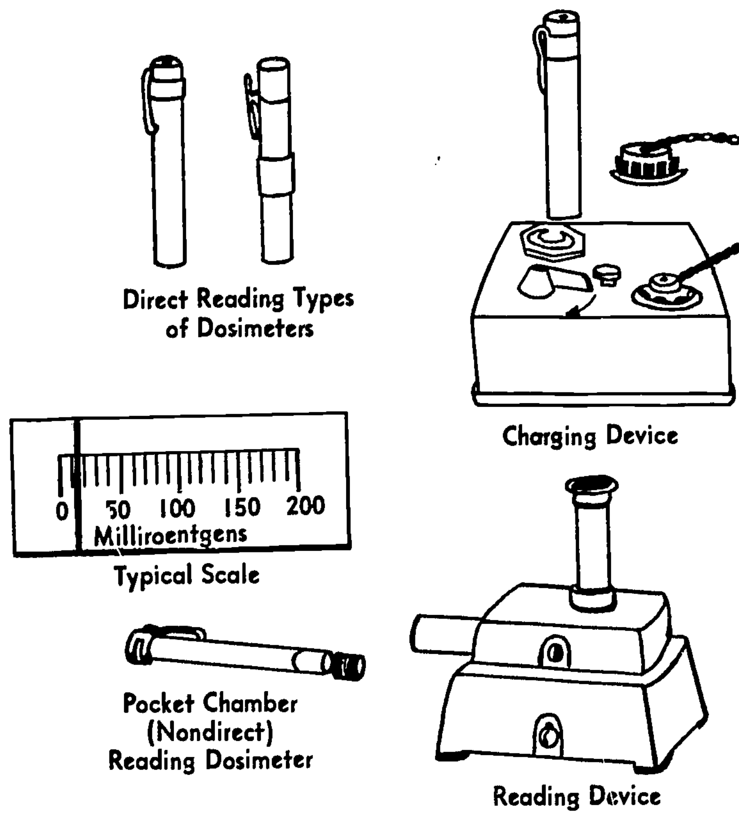


FIGURE 5.4.—Types of Pocket Dosimeters.

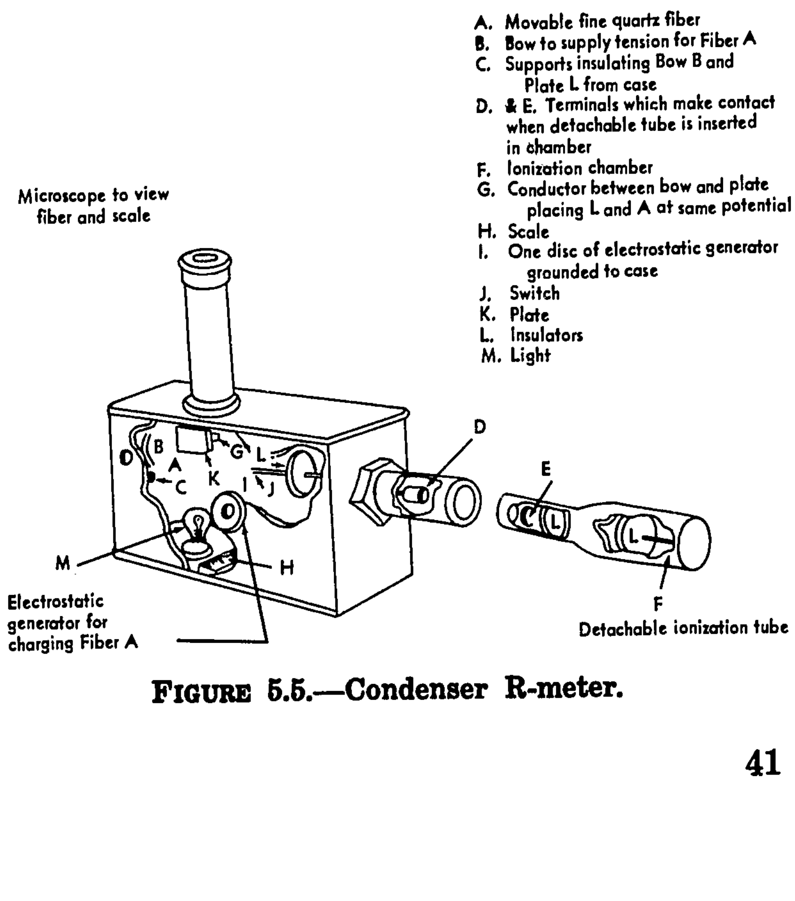


FIGURE 5.5.—Condenser R-meter.

The charged system of the charger and measuring system also is the positive plate of a condenser when it is isolated from the potential of the electrostatic generator. The shell of the charging socket and the mounting barrel that holds the quartz fiber electrometer is the negative plate. If the R-meter and the electrometer of the charger are charged to the same potential (the zero potential of the electrometer) and the R-meter is then exposed to a quantity of X- or gamma radiation so that it is partly discharged; the meter is then reconnected with the charged system of the charger —the charged system of the charger being first "zeroed" and isolated from the generator potential—and the two condensers will come to an equilibrium voltage. This will be indicated by the fact that the image of the quartz fiber will have moved from its zero mark on the reticle of the microscope. Each condenser R-meter is designed to have some maximum measurable amount of radiation.

5–3.4 *Film Badges.* A film badge consists of a small piece of X-ray film inserted in a metal holder. It is worn on the outer clothing and is the most common type of total dose exposure measuring devices. It is used mainly to detect gamma and X-ray radiation and high energy beta radiation. The film badge does not react to alpha radiation.

The badge consists of a metal or plastic jacket in which a photograph or nameplate may be inserted. Inside the jacket are a front and rear filter composed of lead, cadmium, or some other shielding material. Between these are inserted one or more bits of film with varying sensitivities. In one portion of the jacket there is a window to admit low energy gamma rays or beta rays.

After the film badge has been worn for a period of time, several days or weeks, the film is removed and developed by controlled photographic techniques. The film will be darkened in proportion to the amount of radiation received. The darkened film may be compared with a set of control films of the same type which have been exposed to a known amount of radiation. A densitometer is used to measure the density of the image on the film. This measure is then compared with densities of known quantities of radiation of given energies. In this way an estimate can be made on the amount of radiation received by the person wearing the film badge. Obviously, the badge should always be worn by the person when in a radiation area, and it should not be exposed to radiation when not being worn by the person.

5–4 Survey Meters

Although all instruments of the types previously described measure radiation exposure, they cannot be utilized effectively in making a survey of a large area since too many such instruments and too much time would be required. To make a rapid survey of an area another type of instrument is needed, one that instantly measures radiation intensity. Two such instruments are available—ionization chamber instruments with amplifier systems, and Geiger counters.

5–4.1 *Ionization Chamber Instruments.* In an ionization chamber, when ionization occurs in a gas in the presence of an electric field, the ions will move in opposite directions, each going to the electrode having the charge of opposite sign. If the electrodes are connected to a battery, or other source, the ions reaching the electrodes will give up their charge and become neutral again, but at the expense of removing charge from the battery. This results in a current flow through the battery and the external circuit. This current flow, though extremely small, can be measured and interpreted in terms of the radiation intensity required to produce the ionization. Instruments of this type can be made small and portable, and are used for health monitoring and survey work. Their accuracy is plus or minus 15 percent of full scale and they are therefore not suitable for accurate measurements. At the point of measurement, this type of instrument indicates intensity of radiation, an instantaneous measurement.

5–4.2 *Geiger Counters.* In areas where the radiation intensity is low, ionization chamber type instruments are not satisfactory, for they do not provide sufficient amplification of the ionization current to indicate it accurately on a meter. Low intensity measurements are made with Geiger counters which attain their greater sensitivity by taking advantage of all possible amplification within the Geiger tube itself (gas amplification) as well as that provided by electronic amplifier circuits.

In the Geiger counter ionizing radiation creates ions by interacting with neutral atoms. These ions strike other atoms and molecules, and if the ions move slowly their collisions are elastic; that is, they impart some of their energy to each of the gas molecules with which they collide, speeding them up somewhat, but producing no ionization. Another disadvantage of ions with slow speed is the fact that it takes them a long time to reach the electrodes, and they have many opportunities on the way to collide with oppositely charged ions, neutralize each other, and decrease the total ionization within the area. If ions created by radiation move rapidly, however, they in turn strike atoms and molecules with sufficient force to knock electrons out and create other ions, thus increasing the total amount of ionization within the area. Such collisions are called inelastic collisions.

Since it is the ionization that is measured by most of the instruments used for measuring radiation, the greater the ionization, the easier it is to measure the radiation. One of the means of speeding up the ions is increasing the voltage difference between the electrodes and thereby making the attraction of the ion for the electrode greater. It is advantageous, therefore, to secure as high voltage as possible between the terminals in order to gain sufficient speed to produce a large amount of ionization. Another way to speed up ions is to reduce the pressure. This increases the time between collisions and gives the ions enough momentum to make collisions inelastic and produce more ionization. Geiger tubes use these high voltages and low pressures to gain gas amplifications within the ionization chamber itself, and each particle or photon entering the chamber produces an avalanche of ions. This process requires only a fraction of a thousandth of a second, then the system is "quenched" to prepare the instrument for another ray and the resulting avalanche. With further electronic amplification circuits, each avalanche can deflect a needle, produce a click, light lamps, or make any convenient record desired.

Instruments using Geiger tubes as detectors can be made small and portable for safety surveying. Their accuracy is plus or minus 15 percent of full scale and they are not intended to make accurate measurements. These meters indicate dose rates.

5–5 Instrument Characteristics

The radiation measuring devices, previously described, all measure gamma or X-radiation. Since particulate radiation is much less penetrating, the particles cannot pass through the walls of most of the devices, except those designed with a thin window. Such detectors usually have a shutter that can be opened to admit particles. If the shutter covering the detector is opened, particulate radiation is admitted along with gamma radiation. Measurements made with the shutter both opened and closed allow a computation of the amount or intensity of particulate radiation. Also, film badges have an opening in the jacket and filter to admit beta radiation.

Since both alpha and beta rays present a minor external radiation hazard, and usually cannot penetrate the skin, their measurement is not of much importance to radiographers. However, radiographers should be familiar with the characteristics of instruments and the type of radiation they detect or measure.

Instruments should have suitable ranges for the radiation intensities to be measured. The AEC specifies that instruments used by radiographers should measure as low as 1 mr/hr and as high as 1000 mr/hr. Geiger counters are usually low level instruments and read only to about 50 milliroentgens per hour. The ionization chamber type instrument measures high levels of radiation. Commonly used types of such instruments read up to 500 r/hr.

Geiger counters have a tendency to "block-out" in a high radiation field. This means the needle on the dial will not move above zero. Ordinarily, Geiger counters show a small reading above zero due to background radiation. The person using this type of instrument should be careful not to accept a blocked Geiger counter reading of zero as meaning no radiation is present. Special circuits may prevent this blocking. Ionization chamber type survey meters will not block-out. If they are used in a radiation field whose intensity is greater than the instrument's range, the needle will go beyond the highest scale reading.

Several important characteristics of survey meters should be considered in selecting an instrument. These are summarized as follows:

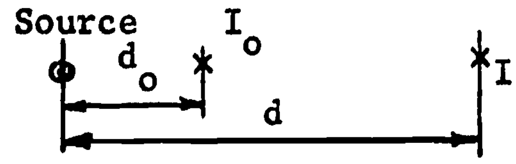
(1) Instruments must detect the desired radiation. Survey meters for radiography must detect X-ray and gamma radiation.
(2) Survey meters must cover a suitable range of radiation dose rate.
(3) Instruments should be stable and hold calibration.
(4) Instruments should have an acceptable time constant. A short time constant is desirable; however, the time constant should not be such that the needle fluctuations would prevent making measurements. (Time constant is an expression of the time required for an instrument to respond to changing signals.)
(5) Batteries must be replaced and therefore should be readily available.
(6) The survey meter manufacturer should maintain a repair and calibration service.

5–6 Instrument Calibration

Radiographers should be able to determine if the survey meters are operating properly. This involves (1) securing a source of radiation for which the intensity is known, (2) placing the instrument at a distance computed to give a desired field intensity, and (3) reading the instrument to determine if it indicates the proper value. Adjustments may then be made on the meter to correct its reading if necessary. The survey meter operation manual will give instructions on how to make the adjustments. It is considered good practice to make these calibration checks at two positions on each instrument scale. One measurement should be near the high end of the scale and one should be near the low end of the scale.

Example: Suppose it is desired to check the calibration of a survey meter which has a scale of 0–1,000 mr/hr. A suitable check point is at 750 mr/hr on the scale. Suppose that a Co–60 source of radiation is available, and from a calibration curve of the source it is determined that the source activity is 3.4 curies. (Co–60 has a dose rate of 14.4 r/hr/c at one foot.) To check the instrument at the 750 mr/hr point, determine the distance from the source at which the gamma radiation intensity will be 750 mr/hr. Then place the survey meter at that distance from the source.

Then $\frac{I_o}{I} = \frac{d^2}{d_o^2}$



where $I_o = 3.4 \times 14.4 \times 1000$ mr/hr
$I = 750$ mr/hr
$d_o = 1$ foot

Solve for d.

$$d = \sqrt{\frac{3.4 \times 14.4 \times 1000}{750}}$$

$$d = \sqrt{\frac{48{,}960}{750}}$$

$d = \sqrt{65}$; d = approximately 8 feet.

At 8 feet the instrument should read 750 mr/hr $\pm$ 15 percent of the full scale reading or $\pm$ 15 percent of $1{,}000 = \pm 150$ mr/hr, this instrument is satisfactory if it reads $750 + 150 = 900$ mr/hr by $750 - 150 = 600$ mr/hr.

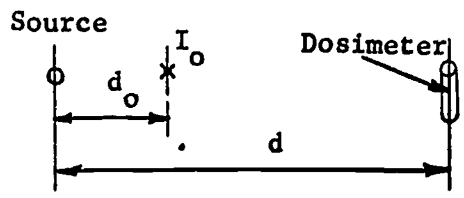
5–7 Source Calibration

Instruments are of great value in calibrating a source of radiation. In this case the type of radioactive material must be known to the radiographer so that a decay curve may be plotted.

Example: Suppose a Co–60 source is to be calibrated. Charge a dosimeter to some low value, e.g., 2 mr. (It is difficult to charge the dosimeter to zero because of electrode discharge upon removal from the charger.) Expose the dosimeter to the source at a measured distance, e.g., 10 feet, for a measured length of time, e.g., 6 minutes. Read the dosimeter. Suppose the reading was 112 mr. From the above information the amount of Co–60 in millicuries may be computed. The source emitted radiation that was absorbed by the dosimeter at the rate of 112 mr − 2 mr = 110 mr in 6 minutes, which would be

$$110 \text{ mr} \times \frac{60 \text{ min/hr}}{6 \text{ min}} = \begin{array}{c}1{,}100 \text{ mr/hr}\\ \text{at 10 feet}\end{array}$$

To compute the mr/hr at 1 foot use the inverse square law.



$$\frac{I_o}{I} = \left(\frac{d}{d_o}\right)^2$$

I_o = to be computed
I = 1,100 mr/hr
d = 10 feet
d_o = 1 foot

$$I_o = I \times \frac{d^2}{d_o{}^2} = 1{,}100 \times \frac{10^2}{1^2}$$

I_o = 110,000 mr/hr at 1 ft.

Since Co-60 has emissivity of 14.4 mr/hr/mc at 1 ft., the millicuries of Co-60 may be found.

$$\frac{110{,}000}{14.4} = 7{,}650 \text{ mc of Co-60}$$

Assume this measurement was made on July 2, 1962.

After making the source calibration measurements, the radiographer should plot a decay curve for that source. The curve sheet must also have information for complete and positive identification of the source. This identification can be made by specifying the radioisotope, the source manufacturer, and the source serial number.

A calibration of this type can be more accurately made with a condenser R-meter. (See Figure 5.5.) Since these are very expensive, most radiographers will not purchase them. Pocket dosimeters are not as accurate as R-meters, but they are much more stable and accurate than survey meters. Dosimeters do have acceptable accuracy for radiography source calibration.

The source activity can be determined on any date by (1) entering the curve sheet at the selected date, (2) following a line vertically to the calibration curve, (3) from that intersection following a horizontal line to the left ordinate, and (4) read the source activity on the scale. (See Figure 5.6.)

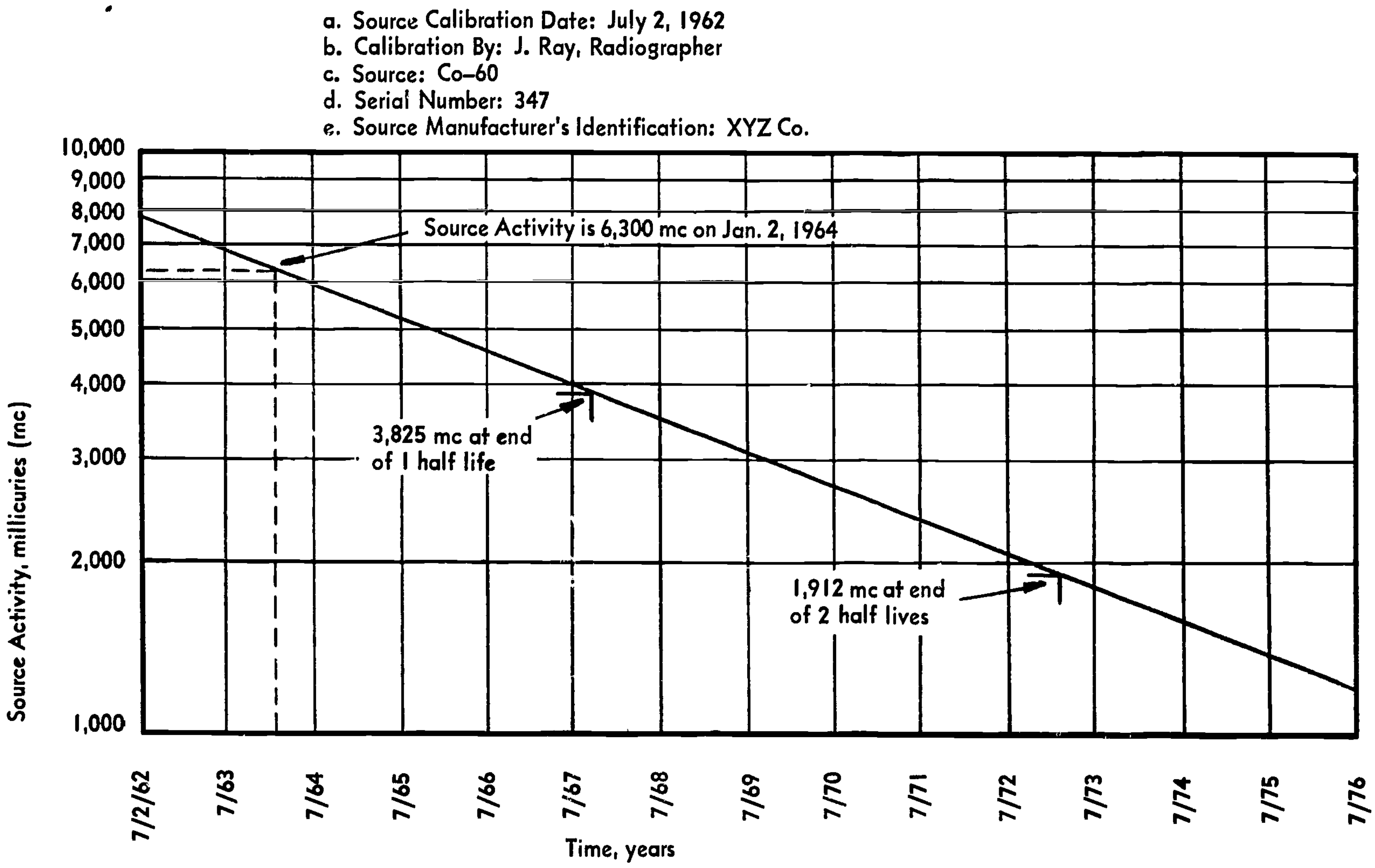


FIGURE 5.6.—Source Calibration Curve.

Part II The Biological Effects of Radiation

It is to be expected that the first question a student contemplating training in the use of radioactive materials will ask is, "What does radiation do to people?" The discussions in Part II are designed to answer this question adequately for most nonscientists.

By now the reader has seen that it is possible to understand the principles of radiation in a general way without extensive study of advanced physics and chemistry. Similarly, a practical knowledge of radiological safety may be obtained by learning of the harmful effects of radiation on living tissues, and of the methods of protection against radiation injury.

Chapter 6

The Nature and Consequences of Radiation Exposure

Part I dealt with certain technical aspects of radiation physics. It was brought out in a general way that radioactivity was harmful to man under certain circumstances. This chapter proposes to acquaint the reader with (1) common types of radiation exposure, and (2) how they are measured. (Also, refer to Chapter 7.) A short statement designed to place the matter of radiation health in proper perspective serves as an introduction to these topics.

6–1 Radiation Health in Perspective

It was only a short time after the discovery of X-rays and of radioactive substances that radiation was identified as a potential health hazard.

The reports (usually dramatized) of illness and body damage sustained by persons handling, or otherwise exposed to, radioactive materials had created a vivid impression on the popular mind even before the Nagasaki and Hiroshima bombs. Since that time there has been so much publicity on the after-effects on the Japanese who were exposed that it is not strange that many laymen tend to regard radiation with awe and fear and to have an exaggerated concept of radiation hazard.

It is true that the biological effects of radiation can be serious, depending on various factors and conditions. However, it is just as true that *radiation can be handled in a safe manner and can be made to perform useful services for mankind.* Since several nations have irrevocably launched an atomic era, it behooves all persons to develop at least a degree of familiarity with radioactivity. Gross ignorance generally results in one of two attitudes, both of which can be deterrents to progress and safety. The first is a blind fear of radioactivity, and the second is complete lack of appreciation for radiation hazards.

In the first instance the individual may be reminded that daily living involves many health hazards as great or greater than radiation. A person hit by an automobile, overcome by a disease germ, or shocked by electricity may experience a biological effect ranging from slight discomfort to death. To harbor a morbid fear of these possibilities is foolish, because they have become a part of everyday life. At the same time, the potential hazard of automobiles, disease germs, and electricity are recognized and proper safety measures are taken. *This is precisely the attitude which should be assumed toward radiation hazard.*

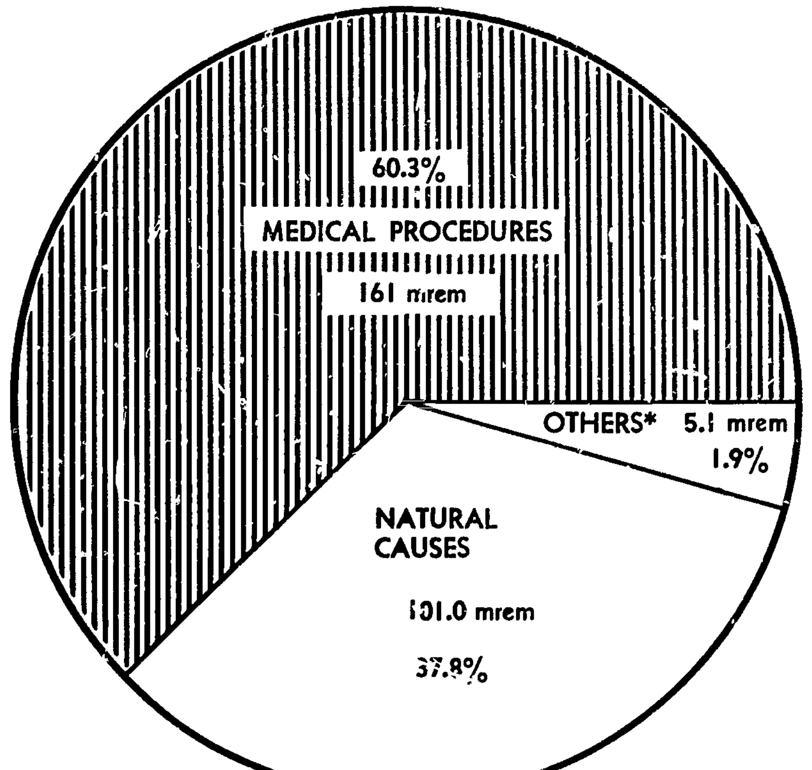
The purpose of this and the following chapter is to acquaint the reader with the effects which radiation produces on the body, so that a proper attitude may be developed.

By way of introduction, it may be observed that all people are continuously exposed to natural radiation. Cosmic radiation from outer space is ever present. At the same time, the earth's crust contains many radioactive elements which find their way into building materials, foods, clothing, and many other items for human use. When radiation for medical reasons is included (X-rays, etc.), it can be seen that humans can and do tolerate considerable radiation during the course of a lifetime. See Table 6.1 for average annual gonad (testes and ovaries or sex organs) exposures in the United States.

TABLE 6.1.—Estimated Average Annual Gonad[1] Exposures in the United States.

	Millirems
Natural Sources:	
(See paragraph 6–3.2 Rem)	
A. External to the body:	
1. Cosmic radiation	28.0
2. From the earth	47.0
3. From building materials	3.0
B. Inside the body:	
1. Inhalation of air	2.0
2. Elements found naturally in people	21.0
Total, natural sources	101.0
Man-made Sources:	
A. Medical procedures:	
1. Diagnostic X-rays	150.0
2. Radiotherapy X-rays, radioisotopes	10.0
3. Internal diagnosis, therapy	1.0
Subtotal	161.0
B. Atomic energy workers	0.1
C. Luminous watch dials, television tubes, shoe fluoroscopes, radioactive industrial wastes, etc.	1.0
D. Radioactive fallout:	
1. External dose	3.0
2. Internal dose	1.0
Subtotal	5.1
Total, man-made sources	166.1

[1] Testes and ovaries (sex organs).



*OTHERS

4.0 mrem Fallout from nuclear tests

1.0 mrem Luminous watch dials, shoe fluoroscopes, TV tubes, radioactive industrial wastes, etc.

0.1 mrem Occupational exposures in atomic energy work

5.1 mrem

FIGURE 6.1.—Estimated Average Annual Gonad Exposures in the United States.

Since man lives within an environment which has a natural background of radiation, exposure hazard must be considered in terms of degrees. A parallel may be drawn to exposure from more familiar radiations, such as heat and light. Excessive heat results in severe burns (often fatal), and overexposure to direct sunlight produces, at the least, painful sunburn. Yet both heat and light have extremely beneficial effects in proper dosages. Injuries from ionizing radiations differ in nature from heat and light radiations (they may penetrate beyond surface layers) but, likewise, are harmful only to the extent of overexposure.

Radiation hazards are thus much like all natural and man-made hazards. They must be considered in terms of the goals or objectives sought. Hardly anyone refuses to work in a building because it is wired for electricity. This is true because an unquestioning faith is held that proper measures have been taken to control or harness this source of energy. By the same token, there is no reason why one should be reluctant to work in a building housing radioactive material which is under proper control. In fact, control measures for individual and group protection are likely to be considerably more stringent for radiation hazards than for electrical or fire hazards.

6–2 Sources of Information About Radiation's Effects on Man

A comprehensive body of information on the biological effects of radiation has been assembled as a result of much study and research. Since it is not possible to deliberately experiment on man with radiation, this information has been gleaned from other types of experiments and by chance. Four important sources of data can be accounted for as follows.

6–2.1 *Animal Experiments.* All of the radiation effects which are produced in man can be produced in animals. Thus, many types of experiments have been conducted over the years on many different animals and under all sorts of conditions. The published results of these experiments form a virtual library of information. However, all animal experiments have one major disadvantage—the dose-effect relations cannot be assumed to be the same as those for man. Therefore, the data from animal experiments must be checked with human experience before final decisions as to exposure rates and therapy can be made.

6–2.2 *Occupational Experience.* Before the full effects of radiation were known, certain workers received small doses of both X- and gamma rays at fairly constant rates over long periods of time. Scientists in many instances were able to study and fairly accurately correlate biological changes in these individuals with rate of exposure. In one example of this type, individuals painting luminous dials on watches ingested paint containing radioactive material by pointing their brushes with their tongue and lips. Many of these persons developed serious pathological conditions which were detected and studied years later. In other examples, miners in uranium mines developed lung cancer after inhaling gases with high concentration of radon. Persons working with X-ray and similar equipment have also been subject to study, as have individuals accidentally exposed to radiation in work situations. However unfortunate these instances might have been for the subject, each provided certain information useful in appraising the effects of this type of exposure on humans, and aided mankind to this extent.

6–2.3 *Medical Uses.* For well over half a century, X-rays and radium rays have been used in diagnosis and treatment of certain diseases. Radioactive isotopes have been administered internally for diagnostic purposes for almost one-quarter of a century. Each time such applications are made, the opportunity is afforded to study carefully the effects of radiation in controlled quantities and situations. The data recorded from these studies have provided an invaluable source of knowledge of the effects of radiation on humans.

6–2.4 *Atomic Bombs.* The Hiroshima and Nagasaki bombing provided further opportunity to study the effect of radiation on man. Most of the bomb damage was done by fire and blast effect, but 15 or 20 percent of the effect has been estimated to have been done by gamma and neutron radiations emitted during the explosion. The United States Atomic Bomb Casuality Commission has been studying the effects of the bomb on the Japanese since 1946, and has amassed a wealth of information.[1]

In 1954, during the atomic bomb tests at Bikini, a heavy fallout of bomb debris was experienced by a group of natives on a neighboring island. This incident, while completely accidental and regrettable, made it possible to study quite accurately, the effect of varying doses of radiation on individuals. Studies of bomb victims continue and eventually long-term effects will be known.

6–3 Measurement Units of Radiation Doses

It is impossible to measure a quantity of radiation directly since it can bring about a change in matter only to the extent of the energy actually absorbed by this matter. A given biological effect may also depend on the type and energy of the radiation, making possible different effects from equal energy absorption. For the above reasons, it is more convenient and practical to measure exposure in purely physical terms, and then use an additional factor to allow for the relative biological effectiveness of different types and energies of radiation. The terms used in measuring radiation exposure are the following.

[1] Glasstone, Samuel, *ed. The Effect of Nuclear Weapons.* Oak Ridge, U.S. Atomic Energy Commission, 1957.

6–3.1 *Roentgen.* The unit for measuring penetrating external radiation exposure is the *roentgen,* which is abbreviated r (named in honor of the man who discovered X-rays in 1895). The roentgen measures gamma or X-ray radiation in air only, and is defined as the quantity of X- or gamma radiation that will produce one electrostatic unit (esu) of charge, either negative or positive, in one cubic centimeter of dry air at standard temperature and pressure (0°C and 760 mm Hg.). One roentgen of radiation has the ability to produce an amount of ionization which represents the absorption of approximately 83 ergs of energy from radiation per gram of air. (Ionization, it will be remembered, is the creation of ion pairs, i.e., positively and negatively charged parts of atoms, by the interaction of radiation on these atoms.) The roentgen can be subdivided into a smaller unit called the milliroentgen, abbreviated mr, which is one thousandth of a roentgen.

6–3.2 *Rem.* Since the roentgen measures radiation in air only, it cannot be used to measure the biological effects on man. The reason for this is that the amount of energy required to produce an ion pair in animal tissue differs from the energy needed to produce an ion pair in air. The term used for these purposes is called the *rem* (*roentgen equivalent man*). The rem can be sub-divided into a smaller unit called the millirem and abbreviated as *mrem,* which is one thousandth of a rem. A rem is defined as the quantity of ionizing radiation of any type which, when absorbed by man or any other mammal, produces a physiological effect equivalent to that produced by the absorption of one roentgen of X-rays or gamma rays.

6–3.3 *Rad.* The *rad* (*radiation absorbed dose*) has recently been accepted as a unit of measurement for radiation absorbed locally by a person. It is defined as the amount of radiation energy imparted to matter per unit mass of irradiated material. The dose unit, the rad, represents an absorption of 100 ergs of energy per gram of irradiated material at the place of exposure. It has been estimated that a rad results in the ionization of approximately one tissue atom in twenty billion. Obviously, this is a very small amount of energy. One rad can be sub-divided into a smaller unit called the milli-rad, abbreviated mrad, which is one thousandth of a rad.

6–3.4 *RBE.* Knowledge of the biological effectiveness of radiation has considerable practical importance since it determines permissible exposure rates for medical uses and industrial radiation exposure. For example, although both gamma and neutron radiation can produce cataracts, neutrons are approximately ten times more effective than gamma rays. Values of *RBE* (*relative biological effectiveness*) have been worked out by the National Committee on Radiation Protection based on the X-ray as the RBE of one.

In actual practice, the total biological dose for several types of radiation (i.e., when a person receives radiation from several sources) is converted to rem. *The dose in rem equals absorbed dose in rads times RBE.* This procedure may be illustrated as follows: Assuming an individual received mixed radiation comprising 0.4 rad of gamma, 0.3 rad of thermal neutrons, and 0.2 rad of fast energy neutron irradiation, his total exposure would be calculated in this manner:

Example:

Radiation	*Dose in Rad*		*RBE*		*Dose in Rem*
Gamma	0.4	×	1	=	0.4
Thermal neutron	0.3	×	5	=	1.5
Fast neutron	0.2	×	10	=	2.0
Totals	0.9				3.9

In summary, the units of measurement of ionizing radiation of widest acceptance are the roentgen, rem, and rad. The roentgen measures ionization in air due to gamma or X-ray radiation; the rem measures the effectiveness of the different radiations in terms of biological damage and quantity of radiation. The rad measures the energy absorbed by radiation in any material. Values of RBE have been worked out for all sources of radiation for computing total exposure from a given dose.

6–4 The Nature of the Radiation Health Problem

The person who works around, or otherwise comes into contact with radioactive materials may be exposed in two entirely different ways. Radiation originating from a radiation source located outside the body is known as *external radiation* and is probably the most frequently encountered hazard. The second type of exposure is from material taken into the body through the body openings, through abrasions or cuts, and by skin absorption. This is known as *internal radiation.* One can see that these different types of exposure constitute separate radiation health problems. Precautions taken against one type will not necessarily be effective against the second type. For this reason external and internal radiation are separately treated in some detail.

6–4.1 *External Radiation.* There are two commonly known types of external radiation hazards. Both have already been described. The first are the long-range, highly penetrating gamma or X-rays which, the student will recall, consist of very short waves of electromagnetic energy having no mass or weight. The second are the short-range, less penetrating beta particles, which are tiny particles of matter. Because of their low penetration, beta particles contribute very little (excepting skin damage) to the total body effect of external radiation.

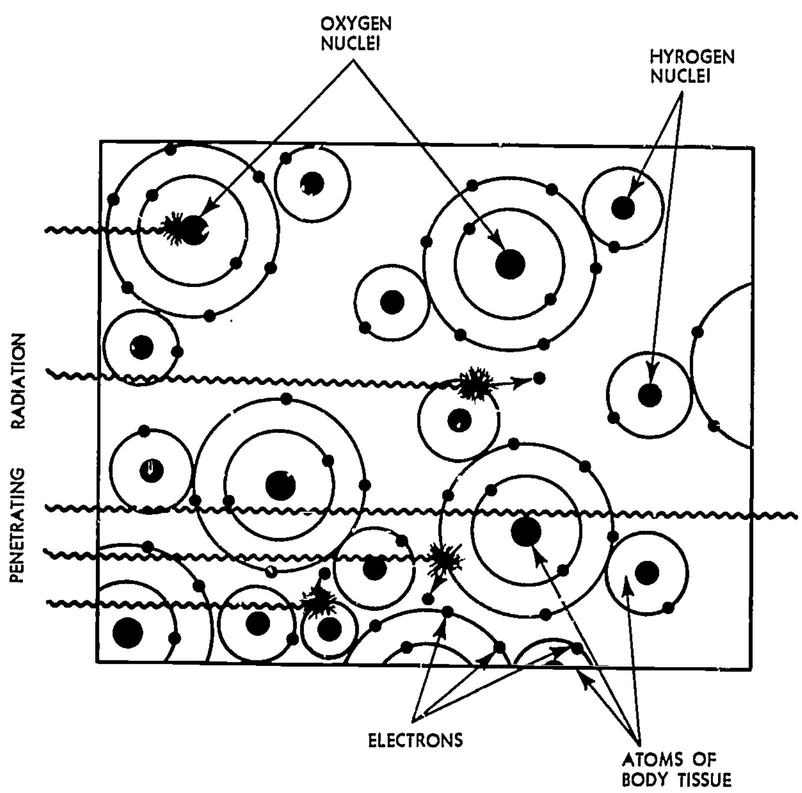


FIGURE 6.2.—Ionization Produced by Radiation Effect on Atoms.

It is common to illustrate the waves of energy from gamma or X-rays as a continuous shower of tiny invisible bullets which may penetrate the body to some depth before causing damage. (See Figure 6.2.) Such an illustration is an oversimplification of course, but it helps to emphasize the point that it is possible for a gamma or X-ray to penetrate various distances into substances (or all the way through) before it hits anything, because of the empty space between atom particles. When a ray hits one of the electrons which is spinning around the nucleus of an atom, a transfer of energy results (the ionization process). (See Figure 6.2.) Ionization can be the cause of complex changes in the body chemistry which result in varying degrees of sickness or death, depending on the amount of exposure.

Neutrons may also produce an external hazard, however, neutrons are less common to industry than gamma and X-rays.

6–4.2 *Internal Radiation.* The internal radiation exposure problem comes principally from alpha particles. These particles do not present an external radiation hazard because they have relatively short range and cannot penetrate beyond the outer layer of skin. The greatest risk thus comes when such materials are taken into the body.

There are four common ways in which it is possible to get radioactive materials into the body: (1) by breathing; (2) by swallowing; (3) through breaks in the skin; (4) by absorption through the skin.

After radioactive elements get into the body, the first question to consider is, "How long will they stay in the body?" A high percentage of everything which is inhaled is exhaled immediately. Materials which are swallowed and which are not soluble in the body's digestive system may be discharged rather quickly through the feces. However, if a material is soluble and goes into the blood stream, it will be carried around the body to the various organs. Since the organs are chemical machines, they chemically respond to the materials. If the radioactive materials are rejected chemically by one organ, the blood stream takes them along to another organ where they may or may not be taken in. If no organ accepts the material, the blood takes it to the kidneys and the kidneys dispose of it through the urinary system. When an organ has use for the material, or if the chemicals of the organ react to the radioactive substances as a material, harmful results may come about. The point to remember is that the organs of the body, initially, are reacting chemically to the element which is carrying the radioactivity, and not to the radioactivity itself.

At any time radioactive materials become lodged in the body organs (as the lungs or liver) irradiation takes place. The damage which may be done depends on the activity deposited, the radiation emitted, the RBE, and at least two other factors—biological half-life and effective half-life.

Biological Half-life. (The radioactive half-life of source materials has been discussed in Chapter 3.) The biological half-life of a radioactive element is that period of time which it takes for one-half the element to be excreted from the body by a natural process. Some materials are excreted quite rapidly and would not remain in the body long enough to do much harm. Others are retained for long periods and can do a great deal of harm.

Effective Half-life. In order to get a working measure of the harm which may come to the body from an internal radiation source, one must combine the radiological half-life with the biological half-life and obtain what is known as the *effective half-life* of the material in the body. The effective half-life of the material may be explained simply as follows. If a material has a radioactive half-life which is very short, then the effective half-life will be more dependent on the radioactive half-life since the isotope would decay before being excreted. If the radioactive half-life is very long, then the effective half-life will be more a function of the biological half-life since the isotope will remain active during its residence in the body.

6–5 Levels and Symptoms of Radiation Injury

A person receiving radiation injury exhibits symptoms according to the severity of his exposure. Certain terms have come into common usage to designate the "gross" condition of injury and to describe the levels of exposure. Although these terms represent arbitrary groupings and classes, they make up a useful vocabulary for describing the level of injury received and the overall condition of the person irradiated.

Doses of radiation are classified accordingly:

6–5.1 *Mild Dose.* A small dose of radiation which produces no detectable clinical effects on the body is considered extremely mild. Such a dose would hardly ever exceed 25 rem, although it might range to 50 rem. Slightly higher doses may produce some changes of a temporary nature in certain body cells, and may possibly produce delayed symptoms. However, it is *improbable that serious effects would result* to the average individual, and this is the criteria used for classifying such dosages as mild.

6–5.2 *Moderate Dose.* Acute exposure with doses ranging from 50 to 200 rem are classed as moderate. When this dose is received there are almost always observable phenomena, although the injury may vary from very slight to serious. The important criterion in classifying a radiation effect as moderate is that there be *some but not excessive* permanent damage. At the lower limit of moderate exposure, symptoms include blood cell changes, swelling, increased acidity and granularity of the protoplasm, crumbling of chromosomes, and halting of cell divisions. At the upper limits of moderate exposure symptoms include nausea, vomiting, malaise, and possible changes in the blood. When dosages approach 200 rem, symptoms increase to include epilation (loss of hair), loss of appetite, sore throat, pallor, diarrhea, and moderate emaciation. These symptoms occur after a latent period of about one week (sometimes longer).

Recovery from moderate doses of radiation is likely unless complications related to poor health, injuries, or infections set in. However, delayed effects of moderate doses may shorten life expectancy as much as one percent and a few individuals may die within two to six weeks after exposure.

6–5.3 *Median Lethal Dose.* When acute exposure results in a dosage from 200 to 600 rem there is a possibility of up to 50 percent mortality. Injury and disability are certain at higher exposures. Symptoms include nausea and vomiting in one to two hours, followed by a latent period of perhaps as long as a week. After this period epilation, loss of appetite, and general malaise accompanied by fever, are characteristic. Severe inflammation of mouth and throat usually occurs near the third week. The fourth week brings on a pallor, petechiae, diarrhea, nose bleed, rapid emaciation, and related symptoms. At the level of the body cell, reproduction (cell division) is permanently affected. General disability may be accompanied by drastic changes in the blood picture, including abnormalities in the red and white cells, platelets, and hemoglobin. It is also probable that intractable anemia will develop, that sterility will result, and that cataract formation will take place. Epilation will be permanent, and many skin changes will take place, with the possible malignant degeneration of some cells accompanied by cancer formation.

6–5.4 *Lethal Dose.* An acute exposure of 600–800 rem or more to the whole body of man is considered a lethal dose. Symptoms are nausea and vomiting in one to two hours, then a short latent period of about a week following which there is diarrhea, vomiting, and inflammation of mouth and throat. As early as the second week, fever and rapid emaciation occur with the probability of death.

6–6 Common Terms of Reference for Gross Effects of Radiation Injury

6–6.1 *Radiation Sickness.* This is a condition produced when a massive overdose of penetrating external gamma radiation is received. Its symptoms are nausea, vomiting, diarrhea, malaise, hemorrhage, and a lowering of the body's resistance against disease and infection. If the irradiation is serious enough it can cause death.

6–6.2 *Radiation Injury.* Radiation injury is the second term commonly used to describe symptoms of radiation exposure and consists of localized injurious effects. Injury is most often to the hand because contact is usually made with the hands. This type of sickness is recognized when injuries not unlike burns occur along with loss of hair and skin lesions. Genetic damage is also a form of radiation injury' which is usually permanent in nature.

6–6.3 *Radioactive Poisoning.* Radioactive poisoning is illness resulting when dangerous amounts of certain types of radioactive materials enter the body. This type of poisoning may cause such diseases as anemia and cancer.

6–7 Summary of Biological Effects of Radiation

The biological effects of radiation were summarized by the Federal Radiation Council in a report to the President dated May 1960. It is apropos to quote the nine points made in this report as a summary of the levels and symptoms of effects of radiation on man.

(1) Acute doses of radiation may produce immediate or delayed effects, or both.
(2) As acute whole body doses increase above 25 rems, immediate observable effects increase in severity with dose, beginning with barely detectable changes to biological signs clearly indicating damage or death at levels of a few hundred rem.
(3) Delayed effects produced either by acute irradiation or by chronic irradiation are similar in kind, but the ability of the body to repair radiation damage is usually more effective in the case of chronic rather than acute irradiation.
(4) The delayed effects from radiation are, in general, indistinguishable from familiar pathological conditions usually present in the population.
(5) Delayed effects include genetic effects (effects transmitted to succeeding generations), increased incidence of tumors, lifespan shortening, and growth and development changes.
(6) The child, the infant, and the unborn infant appear to be more sensitive to radiation than the adult.
(7) The various organs of the body differ in their sensitivity to radiation.
(8) Although ionizing radiation can induce genetic and somatic effects (effects on the individual during his lifetime other than genetic effects), the evidence at the present time is insufficient to justify precise conclusions on the nature of the dose-effect relationship at low doses and dose rates. Moreover, the evidence is insufficient to prove either the hypothesis of a "damage threshold" (a point below which no damage occurs), or the hypothesis of "no threshold" in man at low doses.
(9) If one assumes a direct linear relation between biological effect and the amount of dose, it then becomes possible to relate very low dose to an assumed biological effect even though it is not detectable. It is generally agreed that the effect that may actually occur will not exceed the amount predicted by this assumption.

6–8 Personnel Monitoring

The human senses—hearing, seeing, tasting, smelling, and touching—cannot detect ionizing radiations. Radiation penetrating the body causes no pain and a person can be injured severely without realizing he is in danger. To overcome this condition it is necessary to provide radiation detecting and measuring devices to determine body exposures. To prevent undue body damage the exposure must be limited. Permissible exposure limits have been established by regulatory agencies such as the Atomic Energy Commission and certain State health departments. These limits are rigidly enforced in all industrial radiography installations (see Part IV). In this regard, several types of devices have been designed so that the amount of personnel exposure can be detected and measured (see Chapter 5). These devices are required to be used and careful records should be kept of radiation surveys and personnel exposures wherever radiation work is performed.

The terms reviewed here are associated with personnel monitoring and give something of the philosophy, as well as the practice, of protection from radiation hazards.

6–8.1 *Permissible Exposure.* For practical purposes, the assumption is made that radiation exposure has a "threshold" value, below which no particular effect is experienced by the exposed individual. Strictly speaking, there is no threshold dose for gene mutations, and some scientists thus reject the threshold concept completely. However, threshold values, whether they are interpreted as points where *little or no damage* occurs, are the points of reference used by the government and other agencies in establishing personnel exposure limits. The official definition of permissible dose according to the National Committee on Radiation Protection reads as follows: "Permissible dose may be defined as the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." [2] This definition may be further elab-

[2] U.S. Department of Commerce, National Bureau of Standards. *Permissible Dose for External Sources of Ionizing Radiation.* (Handbook 59) Washington, U.S. Government Printing Office, 1954. Pp. 26–27.

orated to indicate that appreciable body injury means any injury or effect that the average person would consider objectionable, or that medical authorities would regard as being a health detriment.

Permissible weekly dose has also been defined by the National Committee on Radiation Protection: "A permissible weekly dose of ionizing radiation accumulated in one week of such magnitude that, in the light of present knowledge, exposure at this weekly rate for an indefinite period of time, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." [3]

6–8.2 *Exposures Exceeding Permissible Exposure.* The exposure limit of 100 mr/wk can be routinely attained only by carefully planned working procedures. There may occasionally be times when a radiographer needs to work under conditions that require a personnel dose that is greater than 100 mr/wk. Under certain conditions it is acceptable for an individual to receive up to 3 rem of occupational exposure per calendar quarter while working in a restricted area.

This requires that the licensee shall:

(1) Obtain a certificate of information required on Form AEC–4, Figure 13.2.
(2) Calculate the accumulated exposure received by the individual and the additional dose allowed for that individual who is likely to be exposed.

If his "Bank Account," paragraph 6–8.4, permits, the radiographer can be exposed at the greater rate of 3 rem in 13 weeks.

6–8.3 *Maximum Permissible Dose for Occupational Conditions.* The National Committee on Radiation Protection has established maximum permissible accumulated doses to the whole body which it considers safe. These recommendations have been accepted by the AEC and have been written into the rules and regulations of this body, which governs licensed use of radioactive materials. These rules and regulations are given in Part IV, Chapter 13.

The hands and forearms logically are likely to be exposed to more radiation than other parts of the body in an occupational situation. It *is permissible* for the hands and forearms to receive considerably more radiation under AEC regulations because of their known resistance to radiation injury. The annual MPD has been set as 75 rem for these parts of the body. Fluctuations in doses may be treated in the same manner as whole body doses.

(It may be noted that the Federal Radiation Council has recommended that the term "maximum permissible" not be used any longer. Instead, the Council would substitute for MPD the terms "radiation protection guide (RPG)" and "radioactivity concentration guide (RCG)" for maximum permissible concentration. The latter terms are believed to state more clearly the intentions of the standards which have been set. Since most literature used by radiographers uses MPD, this terminology will be used in this radiography training program.)

Occupational exposure may not start before age eighteen. At any age beyond 18 years, the exposure limit is equal to five times the number of years over age 18, provided no annual increment exceeds 12 rems. Thus, exposure of personnel in restricted areas $= 5(N - 18)$, where $N =$ a person's age in years.

6–8.4 *Radiation Banking Concept.* The National Committee on Radiation Protection set the permissible rate of radiation exposure just outlined in accordance with what is known as the radiation banking concept. The idea or model of a radiation bank is used to facilitate the explanation of radiation exposure permitted in a lifetime.

The banking concept considers that each man has a radiation "bank account" to which he adds or deposits 5 rem each year of his life after age 18. He can draw on this account at the rate of 12 rem per year. If he overdraws his account slightly, no particular harm is done, but in order to keep down his exposure to acceptable limits, he should be restricted from additional exposure until his account has been built up by the passage of time. The following example may be used to further illustrate this concept. (Refer to Figure 6.3.) Say a man enters radiation work at the age of 23. Five years have passed since his eighteenth birthday. This means he has banked 25 rem in his radiation bank (5 rem per year). If he is allowed to use up 12 rem of exposure his first year of work, he would then have an account balance of 18 rem, that is 25 rem minus 12

[3] *Ibid.*

Bank Account (rems)

	Age	Deposits (Permissible Dosage Accumulation)	Withdrawals (Dose Received)	Balance
1. a. 5 yrs. × 5 rem/yr.	23	25		25
2. a. 1st year at work			−12	13
b. 6th year over Age 18	24	+5		18
3. a. 2d year at work			−12	6
b. 7th year over Age 18	25	+5		11
4. a. 3d year at work			−12	−1
b. 8th year over Age 18	26	+5		4
5. a. 4th year at work			−12	−8
b. 9th year over Age 18	27	+5		−3
6. a. 5th year at work			0	
b. 10th year over Age 18	28	+5		+2

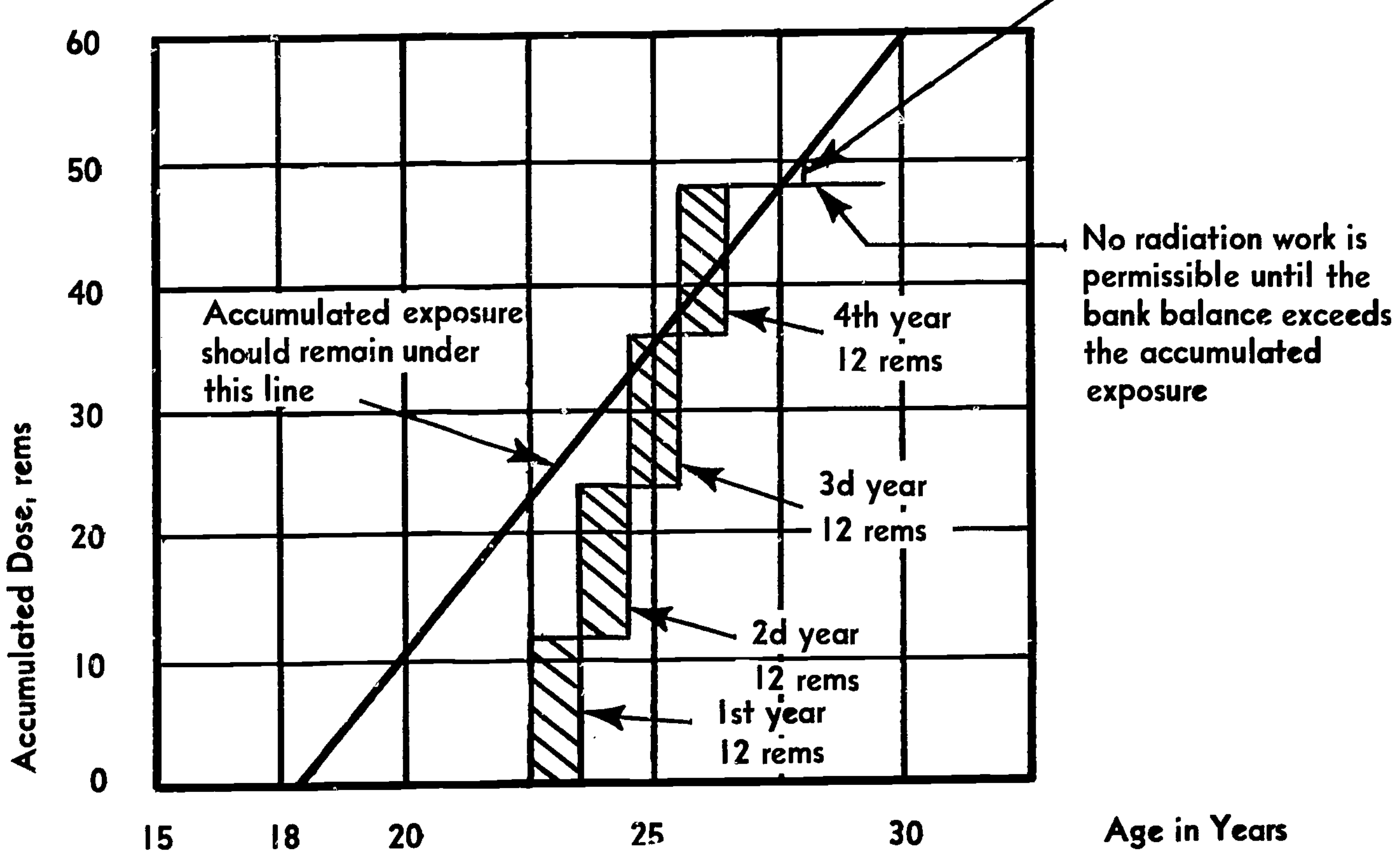


FIGURE 6.3.—Radiation "Banking" Concept for Radiation Workers.

rem plus 5 rem. At the same rate of exposure he would have a deficit in his banking account by the end of the fourth year. This situation would prevent the man from doing radiation work until his "bank account" had accumulated a reserve.

To prevent loss of employment, or job interruptions, the radiation work must be controlled over long time periods so the average occupational dose is not greater than, but preferably less than 5 rems. It should be noted that the average annual exposure in AEC plants and laboratories and industrial operations has been controlled to approximately 100 mrem per week or less.

The average long term exposure limit for industrial radiographers should not exceed 1¼ rem per quarter.

6–9 Exposure for the Total Population

The whole body dose for the population of the U. S. from all sources of ionizing radiation, including medical as well as other man-made sources and natural sources, has been set not to exceed an average of 14 rems per individual over the period from conception to age 30. This means an average of about 0.5 rem per year for the first 30 years. One-third this amount may be added for each decade after age 30 during the reproductive period.

The above limits were established, keeping in mind that, in the genetic picture, it is the average that counts despite very wide variations among individuals. Present estimates place the average dose per person, per generation of 30 years, due to natural background radiation, at about 4 rems, that due to medical X-rays and other non-occupational artificial exposure at about 5 rems. Therefore, it appears that currently the average exposure is well below that considered permissible.

The President approved the *Radiation Protection Guide* prepared by the Federal Radiation Council, and presented in its May 1960 report which is reproduced below. The Council recommended the guide be adopted for normal peacetime use.

TABLE 6.2.—Radiation Protection Guide.

Type of Exposure	Condition	Dose (rem)
Radiation Worker:		
(a) Whole body, head and trunk, active blood-forming organs, gonads, or lens of eye	Accumulated dose	5 times the number of years beyond 18 at 5,000 mrem a year
	13 weeks	3 rem (3,000 mrem)
(b) Skin of whole body and thyroid	Year	30 rem (30,000 mrem)
	13 weeks	10 rem (10,000 mrem)
(c) Hands and forearms, feet and ankles	Year	75 rem (75,000 mrem)
	13 weeks	25 rem (25,000 mrem)
(d) Bone	Body burden	0.1 microgram of radium 226 or its biological equivalent
(e) Other organs	Year	15 rem (15,000 mrem)
	13 weeks	5 rem (5,000 mrem)
Population:		
(a) Individual, whole body	Year	0.5 rem (500 mrem)
(b) Average, gonads	30-year	5 rem (5,000 mrem)

6–10 Physical Examinations

Every Atomic Energy Commission installation has a medical support team. While this may not be true in certain industrial installations, those places operating under AEC licenses should have the services of qualified medical practitioners available at all times. The important responsibility of the medical support personnel is to provide pre-employment and follow-up physical examinations, both of which are important in preventing radiation injury.

The *pre-employment physical examination* is designed to determine the condition of the potential employee's health. A worker in a lab or shop where radiation is present should be in excellent physical condition. Certain physical conditions should exclude individuals from working with radiation.

Follow-up physical examinations are often recommended to assure the continued good health of the employee and to determine that radiation work is not likely to adversely affect his health. After radiation injury, follow-up examinations afford a way of keeping track of the ability of the body to respond favorably to damage.

6–11 Instrumentation

The common types of personnel-monitoring instruments currently used to measure accumulated gamma radiation exposures are the film badge, the pocket chamber, and the direct reading dosimeter. These types of monitoring devices have been described in Chapter 5, but a short review is presented here. Film badges are packets of film (similar to dental film packets) worn in a special holder. The film is sensitive to radiation in various ranges and when developed according to standard techniques will be darkened in relation to the amount of radiation received. The amount of radiation which the film badge has received is indicated when the darkening of film is compared to the darkening of similar films which have been exposed to known quantities of radiation. The film badge is a good indicator of exposure if it is worn continuously while at work and if it is not exposed to radiation when not being worn.

The pocket chamber and direct-reading dosimeters are devices which measure accumulative records of radiation exposure when properly calibrated, charged, and used. Dosimeters, after charging and exposure, can be read directly by holding them up to the light. Pocket chambers, after charging and exposure, must be read in a reading device provided for the purpose. (Dosimeters sometimes give false high readings when dropped or damaged by electrical leakage. Therefore, it is customary in some operations to wear them in pairs.)

Survey meters, paragraph 5–4, are used to survey the radiation fields to determine the radiation intensities. These measurements will give information required for calculating personnel residence time in radiation areas.

6–12 Contamination

Wherever radioactive materials are used there is always the possibility that these materials will be released and the area become contaminated. (Contamination is the uncontrolled release of the radioactive material. Radiation emitted through the walls of a capsule *is not* contamination.) Like all other radiation problems, contamination may be minor or extremely severe, depending upon the chemical nature of the material, the type of radiation given off, the amount released, and requirements for use of the area. For instance, in a laboratory doing very precise radiation measurements, a very small amount of radioactivity is all that is needed to seriously affect the work being performed, an amount that may not be considered harmful to a person.

The hazards from radioactive contamination emanate from alpha, beta, or gamma radiation. The alpha emitter, due to its very short range in air, will do no harm as long as it remains on a surface, such as a wall or floor. However, it may be taken from such places by air circulation or body contact and ingested into the body where great harm may be done. Beta emitters also present the possibility of becoming airborn and taken internally, but may also create high radiation levels near the surface of the contaminated area as well. Gamma emitters represent the greatest danger for *external radiation* as contaminants.

Great care should be taken to avoid contamination.

Contamination should never be a great problem in radiography operations if proper safety precautions are followed. Radiography sources are designed and fabricated to seal the radioactive material in a capsule to prevent contamination. If equipment and procedures properly protect this capsule from breaking, corroding, and wearing there should be no contamination released. Leak tests, called wipe tests, are made at intervals not exceeding six months to assure the capsules have not ruptured and released contamination.

Chapter 7

The Effect of Radiation on the Organs and Tissues of the Body

(It is not mandatory for the radiography technician to be tested on this material. However, it is desirable for all radiation workers to be familiar with the body effects that can occur from unnecessary exposure.)

This chapter deals in a specific sense with the effect of radiation on the various parts of the body. A brief review of the nature and composition of the various tissues and organs is included so that the non-technical student might better understand the rather complicated processes involved.

7–1 Radiation Effects on Living Matter

The body of man, as that of all living organisms, is composed of cells. Cells are the fundamental units of structure of living organisms, just as the atom is the fundamental unit of chemical structure. It is not possible to describe the make-up of various types of cells in a brief treatise such as this, but in general a cell may be described as a restricted mass of protoplasm differentiated into cytoplasm, nucleus, and a binding plasma membrane.[1]

It is well known that the bodies of living organisms have varying tolerances to all kinds of injuries or abuses. The body is able to recoup the damage done to it through a complicated biological process known as mitosis. This is a process whereby cell division takes place and, among other things, wornout or damaged cells are replaced to make the body functionally whole again. Mitosis is, of course, basic to all reproduction, but hereditary and other functions are beyond the scope of this chapter.

Cell division is especially rapid in the earlier years of life before full maturity has been achieved. However, this process never ceases, though it continues at a slower pace after the individual has reached his adult stage. The differential rate of mitosis explains the difference in time which is necessary for an older person and younger person to recover from fractures and other types of organic pathologies.

[1] Johnson, Willis H., Laubengayer, Richard A., and DeLanney, Louis E. *General Biology.* (Revised edition) New York, Holt, Rinehart, and Winston, 1961. Pp. 11–26.

Radiobiologists have determined that radiation affects the living organism principally by altering the ability of cells to reproduce normally. In other words, the radiation damaged body cells do not reproduce in the same manner as healthy cells. This alteration comes about through the process of ionization. Ionization is the result of a transfer of energy which takes place when radiation from radioactive materials interacts with an electron spinning around the nucleus of an atom. Since each body cell is made up of literally millions of atoms, radiation effects are produced by changing the structure or electrical charges of the atoms of the irradiated material. These changes in turn affect the forces (valence bonds) which bind the atoms together into molecules, and the latter break into parts, some of which are charged. The charged parts react immediately with adjacent atoms and molecules while those not charged may interact chemically after a while with the new molecules formed by the charged fragments.

The above process may be illustrated as follows. Because living cells are mostly water, radiation passing through a cell is most likely to strike water molecules (H_2O). When this occurs the bonds between the hydrogen and oxygen atoms of the water are altered and breakdown products are produced which, when combined with oxygen atoms, produce bleaches. Bleaches, such as hydrogen-dioxide (HO_2) and hydrogen-peroxide (H_2O_2) are powerful enough to break down the highly complex protein molecules in the body cells. The all-important enzymes are made up of one class of protein molecules, and the bleaches produced by irradiation remove the hydrogen atom from the sulfur-hydrogen-sulfur bond of the enzyme, thus completely destroying its control function in cell division.

It does not take a great deal of imagination to envision that even a small change in the rate of cell division for a few cells can have many serious effects. One outcome of irradiation is for the cell to continue to grow until its size is abnormal. When such an enlarged cell dies there is no replacement to fill the void it leaves in the tissue. Another effect is that the cell is so altered that its daughter cells are genetically different from it. These daughter cells may die before they reproduce themselves, or their rate of division may be higher or lower than that of parent cells. In either case, an abnormality results.

In summary, the effect of radiation on a living organism is produced at the cell level, and is both physiological and morphological in nature. In humans and other organisms, only those rays which strike a target, that is an electron, cause damage. The degree of damage depends on many conditions and factors, as will be shown in the descriptions which follow.

7–2 Radio-Sensitivity

It is well known that the different tissues and organs of the body differ in nature, function, and appearance. They also differ in their response to radiation. This difference is defined as *radio-sensitivity.* Scientists have determined that "the radio-sensitivity of a tissue is directly proportional to its reproductive capacity and inversely proportional to its degree of differentiation." In simple terms, this finding establishes that the body cells which are most active in reproducing themselves, and the cells which are not fully mature, will be most harmed by radiation. From this fact it can be immediately deduced that certain organs and tissues will be more likely to receive damage after radiation exposure. The likelihood that children will receive more injury than adults also stems from this knowledge.

Several factors besides reproductive capacity are significant in radio-sensitivity. Among the most important are: (a) the stage of cell division, (b) cell activity, and (c) the blood and food supply of the cell. With regard to the first factor, cells are considerably more sensitive to radiation at certain stages of the mitotic process, i.e., while they are dividing. This phenomenon can be understood in terms of the immature state of the daughter cells which are in the process of formation. The situation is paralleled in a newborn baby's greater susceptibility to exposure.

The greater vulnerability of cells which are active is also easy to understand. These cells have a higher metabolic rate (the rate at which chemical changes occur in living cells), which lowers the cell's resistance to radiation. This is simply to state that working cells are more likely to be damaged by irradiation. A knowledge of this fact explains why the resting cells in the blood-forming tissues and gonads, for example, are not as sensitive to radiation as the active cells in these places.

Undernourished cells (those short on blood and food supply) react somewhat counterwise to what might be expected. Rather than present a high susceptibility in their weakened condition which might encourage radiation damage, these cells usually are less sensitive to radiation than normal cells. Their resistance is accounted for in terms of decreased activity, which means that chemical and other changes which radiation might aggravate are slowed down.

7–3 Classification of Body Cells in Order of Radio-Sensitivity

A knowledge of the rank order in which cells are likely to be injured is important to the therapist, who has in mind the special function of each class of cells. It is also well that a person contemplating working with radioactive materials have some acquaintance with the sensitivity of various body cells. The study of radiation damage to body cells has enabled the classification of cells according to their sensitivity in a general way. A partial list, including the most important cells, is given here. The function and importance of each class of cells will be elaborated in the discussion of radiation effects on organs and tissues which follows.

(1) *The lymphocytes, the white blood cells formed by the tissues of the spleen, lymph nodes, etc., are the most sensitive to radiation.* These cells are so sensitive to radioactivity that they are often used as indicators of radiation injuries. A sample of blood is taken and a count of the number and type of lymphocytes is made to determine variations from normality.

(2) *The granulocytes, white blood cells formed in the bone marrow, are also high in radio-sensitivity.* These cells are used to combat bacterial infections of one type or another, and any impairment of their function can be critical to health.

(3) *The basal cells, so named because they are the originators for the more complex specialized cells of the gonads, the bone marrow, the skin, and the alimentary canal,* also rank among the cells highest in sensitivity to radiation.

(4) *The cells in the lungs which absorb oxygen from the air and release carbon dioxide from the blood* are fairly high on the radio-sensitivity scale. *These cells are known as the alveolar cells.*

(5) The *bile duct cells* are intermediate in the order of radio-sensitivity. *These cells perform an important function associated with digestion.*

(6) The cells of the *tubules of the kidneys* are also affected rather quickly by radiation. The importance of the kidney is well known.

(7) The cells that *line the closed cavities of the body,* such as the heart and the blood vessels, and which are known as the *endothelial cells,* are moderately radio-sensitive.

(8) The structural cells of the tissues *which support the organs and other specialized tissues of the body, known as the connective tissue cells,* are more resistant to radiation than the endothelial cells.

(9) The *muscle cells* rank next in order and are quite resistant to radiation.

(10) *The bone cells and the nerve cells* are characterized by the least radio-sensitivity of all body cells.

7–4 Types of Biological Effects of Radiation

Biological effects of radiation are grouped into two major classes. The first and most obvious effects are those which are experienced by the irradiated individual. These effects, known as *somatic effects,* include such things as damage to body tissues and organs which impair normal functions. The second class of radiation effects does not concern the majority of persons but is nevertheless profound. It includes the *genetic effects,* or those effects which may be produced on future generations, if radiation produced changes in germ plasma which can be transmitted to future generations. Both classes of biological effects are considered in some detail on the following pages.

7–5 Factors Related to Somatic Radiation Effects

Somatic radiation effects, as noted, are those experienced by irradiated individuals. These effects cannot be fully understood without some notion of the factors, besides the actual dose, which combine to produce the final reaction. Dosage is of great importance as was brought out in Chapter 6.

7–5.1 *The Rate at which the Dose is Administered.* The living tissues of the body usually begin repair processes as soon as some degree of damage, by whatever means, has been received. This is true in the case of radiation exposure. Up to a point, the body can keep up with such damage, even though exposure is received daily. When the body is able to keep up with damage received no visible change can be observed in the individual. This is why it is possible for a person to be exposed to considerable amounts of radiation over a period of time without bad aftereffects. However, the same amount of radiation given all at once would produce a violent reaction. It is thus the *rate of exposure* that is the first factor to be considered in assessing the effects of radiation.

7–5.2 *The Extent of the Body Irradiated.* Under circumstances of exposure where the whole body receives a large or even a moderate dose of radiation, a severe reaction will be observed and it is probable that further illness will ensue. On the other hand if only a small fraction of the body is irradiated, as in X-ray therapy, the effects on the whole body are very mild, even for considerable doses. Local effects may be quite noticeable, of course, with the possibility of a degree of permanent change in the affected tissues.

7–5.3 *The Part of the Body Irradiated.* Certain portions of the body are more sensitive to irradiation than others. In general, reaction is much more severe if the dose is administered to the upper abdomen (and possibly to the spine) than elsewhere on the body. It is in this region, of course, that most of the vital organs and tissues are found. Thus in considering the condition of exposure of an individual, an attempt should be made to determine what part of the body received the damaging rays.

7-5.4 *The Age of the Individual.* It has been pointed out elsewhere that the physical maturity of the individual is important in radiation. This is true because the cells of persons growing physically are in an accelerated stage of reproduction. For this reason an exposure of a given amount should be considered more serious for a young person than for an adult.

7-5.5 *The Biological Variation Among Individuals.* Individuals differ in various ways in the make-up and functioning of their bodies. Therefore it is not unexpected that a set dose of irradiation may produce a certain effect in one individual which may not be experienced to the same degree by a second person. (For example, experiments have shown that a single dose results in the death of a group of rats; whereas some other rats will die from an exposure of only half this strength.)

7-6 Specific Effect of Radiation on Various Organs and Tissues of the Body

The point has been made that radiation injury depends upon the radio-sensitivity of cells making up the organs and tissues of the body. Level of injury is thus closely related to the organs and tissues which may be exposed to radioactivity. Radiation can cause injury in several ways: (a) There may be damage to a tissue or an organ which results in an increase or decrease in the production of its products, for example, hormones, enzymes, etc.; (b) Radiation may cause an alteration of the birth rate of cells in the tissues or organs; (c) Radiation may cause the complete death of tissues or organs.

Whatever the effect, there is always a chain reaction with other parts of the body which results in some change in non-irradiated tissues and organs. For one thing, unless the damaged tissue or organ is completely destroyed it will begin a repair process. This repair process, of course, affects the rest of the body because the balance of the body is upset to the degree to which tissue products are used in greater quantities during the repair period.

The organ and tissue growths which are affected most by radiation are treated briefly in the discussion which follows. In each instance, a brief review of the biological composition of the organ or tissue is given in order that a perspective of its function to the body might be developed. It will be noted that the nerve tissue and muscular tissue (including the heart), are not discussed. The reason is that these tissues are generally insensitive to radioactivity. Studies have shown no significant effects on these tissues, other than small hemorrhages, after lethal doses of radiation.[2]

7-6.1 *The Blood and Bone Marrow.* Most of the different types of blood cells are formed in the red bone marrow. When these cells pass into the blood stream they travel to all parts of the body, through the arteries, capillaries, and veins. The blood itself is considered a tissue, with the liquid part of the blood, the plasma, serving as a matrix for the formed elements or cells scattered in it.[3] Adults generally have from five to six liters of blood in their bodies.

The formed elements or cells of the blood are classified under three general types: the red blood cells or corpuscles known technically as *erythrocytes;* the white cells or corpuscles known as *leucocytes;* and *platelets* or *thrombocytes.* It has already been noted that the different cells, including the blood cells, do not react to radiation in the same manner, i.e., they have different degrees of radio-sensitivity. This difference, plus the difference in the life span of the various cells, are important factors in radiation injury.

When the body is irradiated the first cells to be affected, by a reduction in number, are the leucocytes. It may be noted that these white blood cells are typical cells with nuclei but contain no coloring matter, thus their name. They are far less numerous in the blood stream than the red cells, being outnumbered by the latter at the ratio of 600 to 1. When the body becomes diseased or injured the number of these white cells increases, apparently to counteract infection. There are two main types of leucocytes, differentiated on the basis of whether they do or do not have granules in the cytoplasm (the liquid surrounding the cell nucleus). The granular leucocytes include the lymphocytes and monocytes. The lymphocytes are formed primarily in the lymph nodes and the spleen, as mentioned previously, and make up 20 to 25 percent of all white cells. Their function is not too clearly established, but it is believed that they may become connective tissue cells

[2] Behrens, C. F. *Atomic Medicine.* New York, Thomas Nelson and Sons, 1949.
[3] Johnson, W. H. *et al. Op. cit.,* pp. 173-190.

and play a role in scar tissue formation. Some recent studies indicate that the lymphocytes give rise to one of the proteins of the blood plasma globulin, which is associated with immune substances or antibodies.

The first cells to be reduced in number after a person becomes irradiated are the lymphocytes, because of their extremely high radiosensitivity. Within a few days the granulocytes count is also lowered. (There are three classes of granular-leucocytes: eosinophils, basophils, and neutrophils.) The lack of the necessary number of white blood cells brings on the condition known as leukopenia which may or may not be serious.

The second part of the blood to be affected by radiation is the platelets. These small structures have no nuclei and are considered as cell fragments which originate from the giant cells of the red bone marrow. Platelets disintegrate in drawn or exposed blood and play an important part in blood clotting.

Within a week after acute or severe radiation, the platelets in the blood stream are reduced critically in supply. This result comes about because of damage to the cells which produce platelets and because of injury to the platelets themselves. Irradiation serves first to activate the platelets, producing a temporary acceleration of blood clotting. Following this phase, the platelets are severely reduced in supply and the blood clotting function is not performed as quickly.

About seven weeks after irradiation, a loss of red blood cells (erythrocytes) occurs. In the adult, all red corpuscles (or cells) are formed in the red marrow of bone. They are developed into typical cells with nuclei, although the nuclei of these cells are excreted just before they are put into circulation It is hypothesized that the excretion of the nuclei allows the cells to contain more hemoglobin, the important oxygen-carrying pigment. Recent work with tracer elements indicates that the red blood cells may function in the blood stream for about 120 days. The total number of red cells in one person is normally about 35 trillion. A lack of the proper number of red cells, or a decreased amount of hemoglobin in the circulating blood, results in a condition known as anemia. Anemia symptoms are pallor, shortness of breath, fluttering of the heart, and general weakness of the individual.

It should be remembered that exposures to radiation at less than permissible levels may not be serious. Under usual conditions cell production in the marrow and in the lymphatic tissue will increase at least temporarily to combat infection, and after the infection subsides these tissues return to a steady, normal level of production. However, repeated small radiation injuries may overwork the repair processes and produce great instability in the blood-forming tissues. Such instability may result in anemia or leukopenia or leukemia. The latter is an acceleration in production of leucocytes, and is almost always fatal. It is significant that repeated small doses of radiation may be more dangerous to a person than an acute exposure which produces severe depletion of all blood cells. The body will probably heal from the latter if there is no further exposure, while injury from chronic exposure is likely to be permanent.

In summary, irradiation damage to the blood and bone marrow may be said to come about because the functions of the blood have been impaired. These functions are carrying food, carrying oxygen, carrying wastes, fighting bacterial infection, and blood clotting. Said another way, radiation effects on the blood and bone marrow are such as to: (1) make the body susceptible to ordinarily harmless bacteria, (2) prevent clotting and thus prolong the healing of open wounds, and (3) bring on a serious pathological condition.

7–6.2 *The Lymphatic System.* Lymph is a liquid which is the same as the blood plasma minus most of the blood proteins. It bathes all of the cells of the body and is often referred to as the internal environment of the cells. All substances that are exchanged between the blood and the cells, and vice-versa, must be diffused through the lymph. A lymphatic system has evolved in all vertebrate types which carries the lymph back into the venous circulation. In man, there are numerous lymph capillaries which join to form even larger vessels (lymphatic vessels) most of which empty into a main lymphatic vessel, the thoracic duct. The thoracic ducts empty into the veins near the heart.

Lymph is found not only in the lymphatic vessels but also in various cavities of the body such as the coelomic, or main body cavity, the pleural (lung) cavities, the pericardial (heart) cavities, and the cavities of the joints, where it serves as a lubricant.

The lymphatic system performs the function of purifying the lymph of tissue debris and of invading bacteria and passing it back into the blood. The lymphatic vessels carry the contaminated lymph to the lymph nodes where these foreign materials are filtered out and the supply of lymphocytes is replenished.

The spleen is the largest mass of lymphatic tissue in the body. However it is involved in blood rather than lymph circulation, and is an important source of lymphocyte cells, as mentioned before. This organ also removes dead blood cells from the blood and stores red blood cells for use in an emergency. Contraction of the smooth muscle in the spleen squeezes the cells into the blood stream at a time of need.

The functions of the spleen can be taken over by other lymphatic tissues in an otherwise healthy man. However, if there is radiation injury, all the lymphatic functions might be lost to the body. This means that the production of lymphocytes would be stopped or reduced, and that the filtering of foreign substances out of the lymph would be impaired. Such a development would be associated with an increased activity of bacteria and would decrease chances of recovery.

7–6.3 *The Skin and Hair Follicles*. The *skin* (or integument) is composed of two main parts, a comparatively thin outer layer known as the *epidermis*, which is free of blood vessels, and an inner thicker layer, the *dermis*, which is packed with blood vessels and nerve endings. The epidermis is made up of several layers of different kinds of cells which vary in number in different parts of the body. The outer layers of the skin are constantly peeling off and being replaced, a process everyone has observed on parts of his own body.

The entire skin, except the palms of the hands and the soles of the feet, is equipped with countless hair follicles. These are inpocketing of cells from the inner layer of the epidermis. Such cells undergo division and give rise to the hair cells, just as the inner layer of the epidermis gives rise to the outer layers. The hair cells die while still in the follicle and the hair visible above the surface of the skin consists of tightly packed masses of their remains. Hair, then, grows from the bottom of the follicle, not from its tip.

Fingernails and toenails also develop from inpocketings of cells from the inner layer of the epidermis. The nails are composed of densely packed dead cells which are translucent. Oil and sweat glands are also derived from the inner layer of the epidermis by inpocketings which go deep into the dermis. Each hair follicle is associated with an oil gland.

The skin has several important functions. Perhaps the most vital, and certainly the most obvious, is that of protecting the body against all sorts of hazards associated with the external environment. Since the skin is relatively tough and pliable, it shields the underlying cells from mechanical injuries caused by pressure, frictions, and blows of one type or another. Likewise, the skin protects the body from certain disease-producing organisms and from the harmful ultraviolet rays of the sun. The latter is accomplished through formation of a pigment (tanning). The skin also helps preserve body moisture, and helps regulate the elimination of heat from the body to maintain a constant body temperature. In addition, the skin contains a number of different sense receptors which allow us to feel pressure, temperature, and pain, and in general to discriminate between the various classes of objects which may be touched. Specialized glands such as the sweat glands, oil glands, and mammary glands are also located in the skin.

Everyone knows from experience with cuts and bruises that the skin is easily injured but has a remarkable capacity for local repair. Fortunately for most of us, injury to the skin is usually localized in a relatively small area, leaving plenty of normal tissue to promote healing.

After irradiation, changes are recognizable in the skin within an hour, even when exposure has not been excessive. Skin reaction, observed microscopically, is one of the first clinical indications of radiation exposure. Intermediate dosages of radiation will produce a reddening of the skin known as erythema. This type of reaction indicates the skin is in a partially damaged condition, with some normal cells remaining among the damaged cells. The normal cells, under usual conditions, immediately begin repair, and a fairly rapid recovery may be expected. Large doses of irradiation (chronic or acute) may result in the formation of cancerous cells on the skin. Skin cancer has been observed in humans after four years of careless, over-exposure to gamma radiation. However, when proper precautions are taken, such a development is extremely unlikely. Another skin symptom of irradiation is premature aging. This occurs only after over-exposure for several years.

Irradiation of the cells lining the hair follicles can stop the growth of hair, or at best cause temporary baldness (epilation). The hair begins to fall out after a relatively large dose of beta and alpha radiation and may continue to do so for one or two weeks. In most instances epilation follows the normal pattern of ordinary baldness, with hair falling out first in the spots where hair would be lost as aging progressed. Interestingly, the least affected regions of the body usually are the eyebrows, eylashes, and beard. The other parts of the body, besides the head, may be affected to a greater or lesser extent. In the small group of Japanese survivors of the World War II nuclear blast, 59 percent lost hair from the scalp, 12 percent from the armpits, 6 percent from the eyebrows, and 3 percent from the beard. Even in the most severe among these cases, hair began to return within a few months. However, the characteristics of their new hair differed in some instances from those of the hair which it replaced. For example, some white-haired Japanese exposed to large doses of radiation regenerated black hair. The regeneration of gray hair is more typical according to studies made.[4]

7–6.4 *The Digestive System.* Man is characterized by a tubular digestive tract or alimentary canal which is differentiated into the following regions: mouth cavity, pharynx, esophagus, stomach, small intestine, and large intestine. In addition, several glands make up a part of this system, including the salivary gland, the liver, which is the largest gland in the body, and the pancreas. The digestive tract is located in the body cavity or coelom, and is held in place by the mesentery. The length of the canal in adult man is about 30 feet. The many folds, especially in the intestinal part of the canal, give it a large surface area. The specialized cells in the walls of the canal secrete substances which convert food particles into absorbable material. It is noteworthy that the processes of digestion begin from the initial intake of food and continue to ultimate excretion. Also, the cells of the alimentary canal are constantly being broken free by the passage of food, and must be replaced continuously.

Studies have shown that the first important effects of irradiation on the alimentary canal are impaired secretion of digestive juices and discontinuance of cell production. When cells of the canal break down, larger numbers of them are released from the walls of the canal and, consequently, the folds of the intestines become cluttered with debris. The symptoms of this kind of damage are vomiting and nausea. Continued vomiting produces thirst. The cells exposed by the breakdown of outer protective cells are irritated by digestive juices and produce convulsions of the intestines and diarrhea. Diarrhea is accompanied by loss of blood through the bowels in severe cases. When extensive damage of this kind is done, ulcers may be produced. Ulcer formation is seldom limited to one area and causes further irritation to the intestines, with even more cell damage.

It has been found that cell repair processes following irradiation of the digestive system may not be normal. In certain instances excess tissues are formed. In other instances no cells are produced. All such developments, as other radiation damage, result in the digestive system functioning improperly. The vital nature of this system immediately suggests the seriousness of danger to it.

7–6.5 *The Liver and Gallbladder.* The liver and gallbladder are important to the digestive tract and can be thought of as part of the digestive system. The former, as has been mentioned, is the largest gland in the body. The liver is important to digestion because of its secretion of bile. Bile is stored in the gallbladder, and when needed it passes through the common bile duct into the duodenum. There it acts to emulsify fats in the small intestine. When the fats are broken into tiny droplets there is much more surface exposed to the fat-splitting enzymes. The liver is also important for several other functions. One of the most important is the conversion of glucose into glycogen and the storage of the latter until it is needed by the body. It is released into the

[4] Glasstone, Samuel, *ed. The Effects of Atomic Weapons.* (Revised edition) Washington, U.S. Government Printing Office, 1950.

bloodstream to maintain a constant level of sugar there.

Radiation damage to the liver and gall bladder generally impairs digestion and thus upsets this important function of the body. Internal radiation (from sources taken into the body) is an especially great hazard because the liver tends to concentrate many radioisotopes within itself. Small doses of external radiation (from sources outside the body) apparently do not injure the gallbladder but may cause alteration in the production of fatty acids in the liver, thereby altering the body's metabolism. Large doses of external radiation may have serious effects by producing small areas of dead tissue and hemorrhaging in both the liver and gallbladder.

7–6.6 *The Endocrine System.* Three of the major classes of glands in the endocrine system are especially prone to harm from radiation. These are the adrenal glands, the thyroid gland, and the gonads. The integration of the activities of the various parts of the body is caused by the nervous system and by the products of the various endocrine glands. Secretions of the endocrine glands are known as hormones. Hormones are carried by the blood all over the body, and each hormone serves to regulate a particular body process. All the hormones can be identified chemically as either proteins, amino acids, or steroid compounds. Hormones are powerful and exert their effects even when present in very small amounts. They are necessary to the preservation of health.

The *adrenal glands* are considered first. There are two adrenal glands, and in man one is located on the top of each kidney. The main hormone produced in these glands is adrenalin. The importance of adrenalin is shown by the fact that an injection of this hormone produces marked effects on an individual, including an increase of heart beat, a rise in blood pressure, an increase in the glucose content of the blood, a decrease in the glycogen content of the liver, and an increase in resistance to fatigue. An above-normal supply of adrenalin may produce symptoms such as dilated pupils, hair standing on end, and the blanching of skin.

Leaving the other hormones besides adrenalin, which is found in the adrenal glands, aside for the moment, damage due to irradiation can be shown as follows. The adrenal glands produce and store adrenalin which is released according to the body's needs. Every normal individual has present in his bloodstream varying amounts of adrenalin at all times. Upon stimulation the adrenal glands empty an extra amount of adrenalin into the bloodstream. This brings about the effects noted above. Blood pressure is raised by constricting the blood vessels and stimulating the rate and force of the contraction of the heart. The excess adrenalin also acts within the liver and muscle tissues to cause increased sugar breakdown. Both of these processes provide extra energy to the individual. After each instance of stimulation, tissue function becomes normal again and the supply of adrenalin which has been depleted is restored over a period of time. The interval for this restoration of adrenalin will be longer if the cells of the adrenal glands have been damaged, as they can be through irradiation. Thus the body functions less efficiently, and the individual becomes more susceptible to heat, cold, injury, and infection. His heart beat may become irregular, his blood pressure drop, and the balance of salts in his blood plasma may be upset. At this point a note of caution is in order. The symptoms noted above are not solely attributable to adrenal damage. Caution should thus be used in making a diagnosis.

The *thyroid gland* is located along the sides of the trachea at the base of the throat in man. This gland secretes a hormone known as thyroxin. The general effect of thyroxin is to regulate the rate of metabolism. It may also be noted that the functioning of the thyroid gland is associated with that of the pituitary and the adrenal glands. Damage done to one of these glands will alter the functions of the others and have marked effects throughout the body.

The thyroid itself is not too sensitive to external radiation. However, it is the place in the body where iodine is concentrated. When radioactive iodine, which comprises about 5 percent of the fission products from a reactor, is absorbed by the thyroid, this isotope continuously bombards the cells of this gland with beta and gamma radiation. The radiation damage to the thyroid causes a decrease in thyroxin production. This in turn affects the basal metabolism rate by decreasing it. The next effect is for muscle tissue to fail to absorb needed oxygen and the health of the individual becomes severely impaired.

Although the pituitary glands are not extra sensitive to radiation and thus are not discussed in detail here, it may be noted they are affected by malfunction of other glands. These glands regulate growth, act on the sex organs, and stimulate the thyroid, among other things.

The reproductive organs of man (ovaries and testes) are known as the *gonads*. Radiation may severely damage the cells of these organs and can produce sterility, *although this is unusual*. Moderate doses of radiation, however, will slow down the production of sperm cells in males. Slowing down of sperm production, because of injury both to irradiated cells and to the repair functions of nonirradiated cells, results in only partial sterility. The sperms themselves are radio-resistant, and irradiation of the sex organs does not destroy them.

Under modern conditions of occupational esposure, there is no evidence of any impairment to fertility. Permanent sterility is only produced in either man or woman by near lethal doses to the reproductive organs. Sexual impotency, the physical incapacity to engage in the sexual act, is not necessarily related to sterility, and *is not a usual occurrence*. The latter statement is emphasized because of a great fear which many persons harbor. Individuals rendered completely sterile by irradiation were impotent only while incapacitated by irradiation sickness.

After a relatively large dose of irradiation to the pelvic region, a pregnant woman may have a miscarriage or a still birth. This is not always the case however. For example, of 98 pregnant women in Nagasaki who were within 1000 meters of the center of the explosion, about 23 percent of those who had severe radiation sickness miscarried, compared to 4 percent of those who were not sick. It is possible for children irradiated *inutero* to be abnormal. However, there is little information on this subject. The genetic effects of radiation are so profound that they are discussed under a separate heading (paragraph 7–8).

7–6.7 *The Respiratory System.* Man breathes through his respiratory system which is chiefly composed of the lungs. Normally air enters the human system by way of the nostrils or mouth, passes through the nasal cavities into the pharynx, through the glottis, and into the larynx. From the larynx the air goes to the trachea, which leads to the right and left lungs. The lungs are made up of minute air sacs called alveoli. These sacs are connected to small tubes, bronchioles, that lead into larger tubes, bronchi, which are branches from the trachea. In the process of breathing, each air sac is expanded and compressed by the muscles of the lungs and in this manner is filled with air and emptied. Air is absorbed through the walls of these sacs by tiny blood vessels (capillaries) which deliver oxygen into the blood and absorb carbon dioxide and moisture from the blood. Each air sac membrane is extremely delicate in order to permit the necessary exchange of gases, yet it is strong enough to hold back the blood. If the membranes of these air sacs break or have their permeability altered in some manner, blood may enter the lungs.

Radiation produces its effect on the lungs by damaging the air sacs or the maintenance cells which maintain the membranes. This type of damage may occur from external radiation but the greatest hazard is from internal radiation such as that emanating from inhaled dust and vapors. Small particles of radioactive materials enter the air sacs and may remain there indefinitely. If they do not dissolve, they will cause continuous damage and eventually result in the formation of tumors. Soluble radioactive materials pass through the air sac membranes into the blood to cause damage in other places throughout the body. Although the above is the primary way in which radiation affects the lungs, damage may also occur from toxic byproducts created in other parts of the body as a result of exposure. These substances are carried to the lungs by the blood stream. Any damage to the lungs is reflected in the functioning of the body.

7–6.8 *The Urinary System.* The urinary system of man is made up of kidneys, ureters, bladder, and urethra. The kidneys lie outside the body cavity and are supplied with rather large renal arteries and renal veins. The ureter leads from an indentation in each kidney and is a duct which empties into the urinary bladder. The urethra is a tube which carries urine from the bladder outside the body for disposal. The kidneys help regulate the concentration and content of the blood by excreting water and waste products.

Both external and internal radiation may damage the urinary tract. External radiation breaks down the tissues and reduces kidney functions. Internal radiation sources may become concentrated in the kidneys and cause extensive damage. This is especially true when the radiation source is slow. When blood appears in the urine after irradiation, it is an indication that the kidneys have been injured. This symptom is caused by hemorrhaging in the cells which line the kidneys. Lesser damage to these tissues is indicated by an increase of amino acids in the urine. Radiation damage also breaks down the cells of the uterus and the bladder. When large numbers of cells have died they feel much as the outer skin does after a sun burn. The tubes (ureters) to the bladder may be blocked by clots of these dead cells with the resulting concentrations of wastes causing damage.

A still further symptom of radiation injury to the urinary system is known as *tenesmus*, which is the urge to rid oneself of waste products without being able to do so. In some cases, which are extreme, the bladder may no longer be controlled, possibly because of damage to cells, which normally act as signals to the brain.

Radiation damage to the kidneys does not appear to be completely incurable, although symptoms of slight damage to this part of the body have been observed in persons chronically exposed to small doses of radiation over a period of several years.

7–6.9 *The Bones.* Bones consist of living cells distributed in a matrix of fibers and bone salts. The fibers give the bones their tensile strength. Salts give them their hardness. The cells are connected by fine channels which penetrate the matrix of fibers and salts. Larger channels in the matrix contain the blood vessels and nerves. The center of the bones is filled with marrow, either red or yellow. The red marrow, as pointed out before, has blood-forming functions and is restricted in adults to the skull, breastbone, ribs, pelvis, and spine. The yellow marrow provides fat storage.

Radiation represents a serious threat to the highly radio-sensitive red marrow of the bone cells, as has already been pointed out. However, external radiation has little effect on the bone cells themselves or on the fibers and salts. Internal radiation can affect the bone cells because they absorb certain radioisotopes which may come to them through the blood. Some of these isotopes are so readily absorbed that they are called bone seekers. Such isotopes damage the bone cells, as well as the marrow cells, with their long-term bombardment of radiations. Tumor production is possible under these circumstances.

7–6.10 *The Eyes.* When our eyes function we experience sensations of light, color, and form. The lens system of the eye forms images on the retina, just as they are formed on a screen by a projector. The iris acts as a diaphragm in regulating the size of the pupil and controlling the amount of light which reaches the retina. Of course, the brain rather than the eye interprets the picture that is received.

Unlike other cells in the human body the transparent lens cells cannot be replaced by regeneration. These cells lose their transparency when they become damaged or die and form what is known as a cataract. Although cataracts form slowly, they eventually cause the individual to lose his sight. Scientists are not clear on this point, but it appears that only one or two damaged cells are necessary to initiate a cataract. In some way, by releasing a toxic substance or by preventing a transfer of food to other cells, other lens cells are affected by the damaged cells.

Radiation affects the eye by promoting the development of cataracts. However, it takes a relatively large dose for this to occur. Neutron and gamma radiations appear to be the chief producers of radiation-induced cataracts. Susceptibility to radiation-induced cataracts is greater among younger persons, because their lenses are still in the process of growth. Older persons quite commonly develop cataracts from natural causes. In most instances cataracts can be treated surgically by removal of the lens and the use of eyeglasses to do the necessary focusing of light. Nevertheless, the person who is working with radioactive materials should be aware of this hazard.

7–7 Effects of Radiation on the Life Span

A recurrent question among those persons who work with radioactive materials is, "What is the effect of radiation exposure on the life span?" Unfortunately, a final answer is not available at the present time. In this regard, a report that radiologists died at an earlier average age than the general population has been discounted because of unsatisfactory evidence.

The information obtained from numerous experiments performed with laboratory animals (mostly rats and mice) indicates that exposure to radiation *in sufficient amount* does shorten life. These experiments gave positive results whether or not conditions of daily exposure or of single whole body exposure existed. It was pointed out before that the interpretation of data from animal experiments must be made with great caution, insofar as man is concerned.

Careful analysis of all evidence available suggests that exposure to permissible occupational dose rates from an early age does not shorten life. Nevertheless, there is not sufficient evidence to make an unqualified statement. It is therefore advisable to keep the permissible daily dose for lifetime exposure to penetrating radiation as low as possible.

7-8 The Genetic Effects of Radiation

The study of characteristics inherited in the reproductive process is known as *genetics*. Scientists have determined that in man and all higher animals every individual arises from a single cell formed by the fusion of two germ cells, one from each parent. Geneticists have discovered that such things as type and color of hair, eye color, stature, etc., are controlled by genes. Genes exist in all body cells, but only in the germ cells do they play an essential role in the reproductive process. The genes occur in pairs, with each pair having the ability of producing a physical characteristic of the new individual. In this regard, the cell division (meiosis) by which the sperm and ovum are produced in the male and female, respectively, results in each sperm and ovum receiving only one-half the number of genes that were present in the parent cell. Genes of the male sperm couple with the genes of the female ovum to produce the gene pair which determines the particular characteristics of an offspring. Generally, for gene pairs, one gene will dominate in producing a characteristic, such as eye color. The combination of a gene for brown eyes from one parent with a gene for blue eyes from another parent nearly always results in a child with brown eyes. This is true because the brown eye gene is *dominant* and the gene for the blue eye is *recessive*.

Occasionally a sudden change occurs in a gene and it fails to reproduce normally. The abnormal form is called a *mutation*. Mutations may be passed on to subsequent generations. Mutations, like genes, can be dominant and recessive. Dominant mutations may be passed on by either parent, with the trait, while recessive mutations must await a situation when both parents carry the trait. Variations found among humans are in part the result of hereditary variations coming from mutations which have occurred in past generations. As far as is known, all genes are subject to mutation and, over the population as a whole, mutation is occurring at a constant although very low rate.

The production of gene mutations by radiation has been carefully studied in plants and animals and it has been found that the mutation rate is proportional to the radiation exposure. There has been no such study among men (for obvious reasons) but it is reasonable to suppose that the same general pattern would occur.[5]

Radiation may also produce chromosome mutations. The reader will recall that chromosomes are chains of genes and the radiation effect is to break the chain. The chromosome fragments may then recombine in such a manner as to produce translocations of large groups of genes or other abnormalities, as loss of or duplication of body parts. Also, normal chromosomes are unlikely to pair properly with radiation-altered chromosomes and the fertilized egg will not divide. In other words an offspring will not be produced.

There are two effects on individuals in the reproductive ages who receive a dose of radiation.[6] The first effect is on their immediate offspring and the second is on their later descendants, which is to say on the population as a whole. Although malformed children are cause for a great concern to immediate relatives, it is more appropriate to a discussion such as this to consider the effect of extensive radiation on the population as a whole. As a

[5] Muller, H. J. "The Manner of Dependence of a Permissible Dose of Radiation on the Amount of Genetic Damage." *Acta Radiologica*, 41:5-20, January 1954.

[6] Quimby, Edith H., and Feitelbert, Serger *Radioactive Isotopes in Medicine and Biology*. (Revised edition) Philadelphia, Lea and Febiger, 1963. Pp. 186-187.

matter of fact, it is quite impossible to predict what would occur to a given unborn individual because of the many chance factors. In this regard, it will take years to determine the effects on the children of the Japanese who received radiation exposure from the World War II bombings. However, because of known probabilities, it is possible to estimate within margins of error the effects on a total population.

Roughly two percent of all live births in the United States have some sort of genetic defects, which are related to mutations. These defects range from epilepsy, idiocy, and congenital malformations, to other organic defects. Should every one in the U. S. be subjected once to a doubling dose of radiation (the amount which would eventually cause the complete doubling of gene mutations), the percentage of live births with defects could be expected to rise in the first generation as a result, but could be expected to return to the normal equilibrium later. However, if each succeeding generation of U. S. citizens received a doubling dose of radiation, in a few generations the number of live births with defects would rise to a double level, which in this instance would mean some 200 million children born in a generation with defects.[7] This rate of increase could theoretically be continued to a point which would have very serious implications for a given population.

The question as to what represents a doubling dose of radiation for humans is not easy to answer. This is true because man is not a pure species like a pure strain of fruit flies or mice or some other species which can be studied under laboratory conditions. Also, the time period which elapses from one human generation to another is such that answers to questions must await the passage of many years.

Estimates as to what constitutes a doubling dose of radiation vary from 25 rads to 150 rads. The dose, however, can be delivered at once or in many small portions during the reproductive period of the individual.

It is recomended that a period of at least six months should be interposed between the time of the radiation of the reproductive organs and the conception of a child. This period permits the formation of sex cells which contain proportionately smaller numbers of gene mutations than exist immediately after irradiation. In this regard, the fear expressed in the past (by many reputable persons) that there would be a sharp increase in the frequency of abnormalities has not been validated. The children conceived in Japan after the nuclear attacks by irradiated parents appear normal for the most part.

In concluding this discussion, the reader should be reminded that not all mutations are undesirable. In fact, naturally occurring mutations are responsible for normal evolutionary processes. Radiation simply speeds these processes, increasing the chances of undesirable as well as desirable changes.

[7] *Ibid.*

Part III

Industrial Radiography

The material in Chapters 8 through 12 presents the technology of the program. Radiography is not an exact "science." The technician will soon learn that many conditions cannot be accurately predicted for his calculations. Rules and approximations are suggested to be used until the technician gains ability and confidence. Then he can proceed to make innovations that will improve performance with the facilities available.

The radiographer-trainee is encouraged to study the references listed in the bibliography.

Chapter 8

Introduction to Radiography*

In 1895, Roentgen experimented in Germany with cathode rays. He found, as a result of these experiments, that the vacuum tube he was using to get cathode rays was giving off some kind of new ray. The new type of ray caused a glow to come from a chemically coated paper near by. Further study showed that the invisible radiation, which he called X-rays, could penetrate paper, wood, books, the human body, and even pieces of metal. He also learned that the radiation could affect photographic plates in about the same way as light and that the radiation could produce an image on photographic paper.

After Roentgen's discovery, many scientists began studying X-rays. Soon the term radiography was used in reference to taking pictures of objects with X-rays.

In 1898, the Curies discovered that radium was radioactive. The invisible radiation given off by radium was named gamma rays. No use, however, was made of radium as a source of radiation for radiography until the late 1920's.

8–1 The Process of Radiography

Radiography is a process of testing materials that uses penetrating radiation such as X-rays or gamma rays. This allows examination of the interior of objects or assemblies that are opaque to the light. Radiography is called a nondestructive method of testing since objects that are tested are not damaged by the test and may still be used when the testing is completed.

In passing through the material, some of the radiation is absorbed or changed. The amount of absorption is dependent upon the thickness of the material, the density of the material, and the atomic number of the absorber. Some kind of detector such as film, a fluorescent screen, or a Geiger counter may then be used to record the variations in intensity of the emerging beam as visual images or signals. Industrial radiography is primarily concerned with recording images on film.

*Extracts from *Radiography in Modern Industry* published with permission of Radiography Markets Division, Eastman Kodak Company, Rochester, N.Y.

The three basic essentials in producing a radiograph are:

(1) a source of radiation, usually X-rays or gamma rays
(2) the object to be tested
(3) a cassette containing the film.

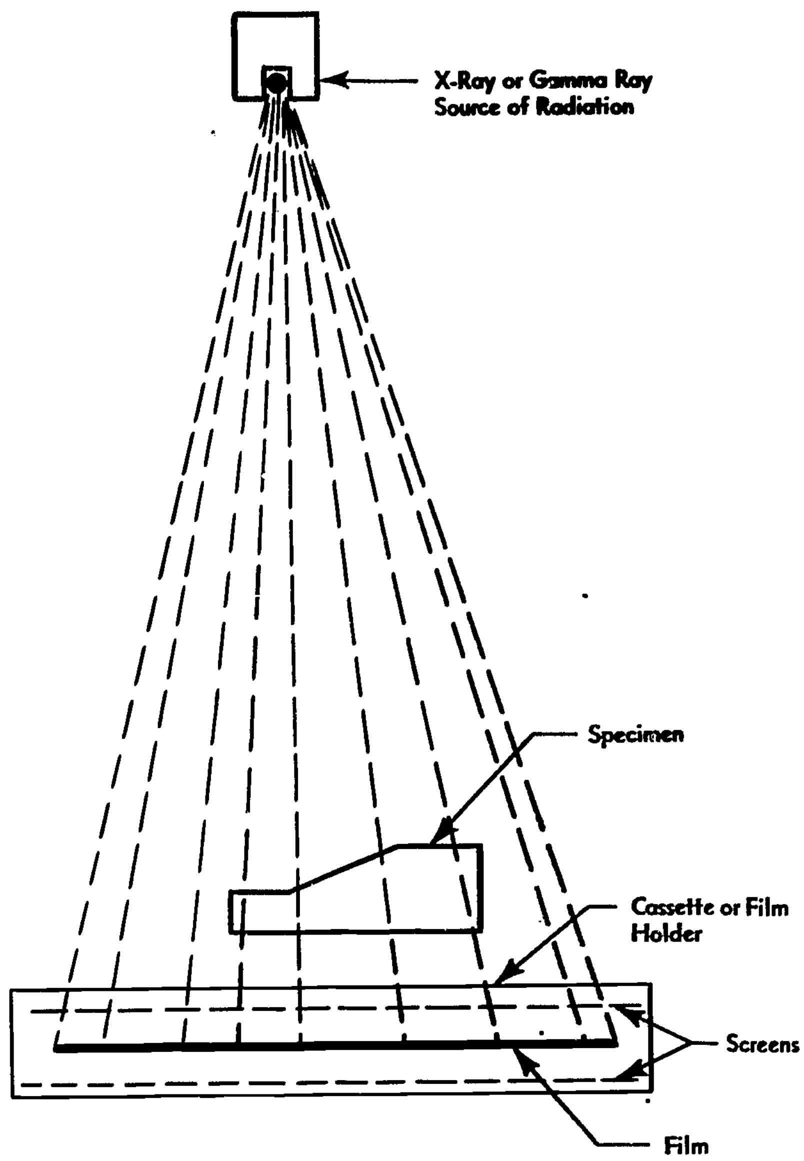


FIGURE 8.1.—Radiograph Exposure Arrangement.

The diagram in Figure 8.1 illustrates the main features in the making of a radiograph. The source of radiation may be an X-ray tube or a capsule containing a suitable radioisotope such as cobalt–60. Whatever the source, the radiation proceeds in a straight line from the source to the object. Some of the rays pass through the object, some are absorbed by the object, and some are scattered in all directions by the object. The amount of radiation reaching the film in the cassette depends upon a number of factors. Among these are the nature of the material being tested and its thickness.

Suppose the object being tested is a piece of steel and it has a gas bubble in the interior. There is a reduction in thickness of the steel through the area of the bubble. Therefore, more radiation will pass through the section containing the bubble than through the surrounding metal. A dark spot corresponding to the projected position of the bubble will appear on the film when it is developed. A radiograph is similar to the negative of a photograph. The darker regions on the radiograph represent the more easily penetrated parts of the object, while the lighter regions represent the thicker or more dense parts of the object.

8–2 The Radiograph

The processed film containing the visible images caused by exposure to radiation is called a radiograph. The darkening of the radiograph is referred to as *density*. This is sometimes referred to as photographic density to distinguish it from the mass density of the object which was radiographed.

Differences in density from one area to another on a radiograph are termed *radiographic contrast*. The density of an area on a radiograph depends upon the amount of radiation the film emulsion absorbs in that area. The more radiation absorbed, the darker the radiograph. Within limits, the greater the contrast or density differences in a radiograph, the easier details may be seen. Too much overall contrast can actually cause a loss in visibility of some details at the very high and very low density levels.

Sharpness of outline in the image on a radiograph is called *definition*. If the change in densities between two areas is a gradual shading without a sharply marked line, then there is low definition of detail. Contrasts are more difficult to detect in this case. Sharply defined images on a radiograph mean a high definition.

When radiation strikes film, only a very small portion of the energy is absorbed. Since the darkening of the film is due to the absorbed radiation, a large part of the radiation energy is lost. One way of using this lost energy is to use *radiographic screens*. These are also called intensifying screens. Lead foil on both sides of the film has an intensifying effect. Lead, upon being excited by radiation, emits electrons. Electrons expose the film just as the X- or gamma radiation; in fact the electrons are more easily absorbed than the radiation. Also, fluorescent intensifying screens are occasionally used in X-ray radiography, but as a rule are not used with gamma rays. These screens consist of a smooth layer of powdered fluorescent chemicals coated on a piece of cardboard or plastic. Such screens may lower the exposure needed to produce satisfactory radiographs by a factor of more than 100.

Contrast of radiographs may be reduced by *scatter*. Materials not only absorb radiation but scatter radiation in all directions. Thus the film receives not only radiation from the primary radiation source, but also scattered radiation from the object being radiographed, the film holder, and the walls and floor of the room. Scattered radiation tends to make blurry the whole image on a radiograph. Scattering may be reduced by screens, masks, diaphragms, and filters.

8–3 Applications of Radiography

Radiography is very useful in inspecting and testing products of various kinds. It may be used to inspect finished products to determine their soundness or fitness and it may be used to help develop production techniques that will produce products that meet desirable standards. This method of testing may be used to examine one or two pieces occasionally or it may be used to examine hundreds of pieces in a short period of time.

Welding has become one of the important processes in the manufacturing of metal products. Due to advances in this field, many high pressure, high temperature tanks or containers are constructed by welding. Such equipment is now almost universally examined by radiography and other nondestructive testing methods. Weld radiography is one of the important applications of industrial radiography.

One of the first industrial applications of radiography was the examination of castings. Most metal produced in the world is cast into a mold at some point in its processing. The cooling of the liquid metal in the mold may be accompanied by several undesirable effects. Small pieces of sand from the mold may become trapped in the metal, gas bubbles may be formed, and slag may be caught in the metal. Also, the shrinkage characteristic of most metals as they cool from a liquid to a solid may lead to cracks, holes, and even breaks. Many of these may not be noticeable on the surface of the casting. Radiography may be used to detect these flaws.

Metal may be worked or shaped into desirable forms. Steel is usually forged at high temperatures because it becomes plastic to some degree and is easier to form. The expansion or contraction of metal being forged may be uneven and the stresses may cause cracks or breaks at certain points in the metal. Radiographs will reveal internal defects.

Nonmetallic materials such as plastics, ceramics, concrete, paper, wood, textiles, and food products are now being inspected by radiography. Assemblies are being inspected. Study of internal working parts may be made during the design and prototype stage as well as the production stage.

Other applications include pipe wall gaging, high speed or flash radiography, microradiography and stero-radiography.

8–4 Industrial Radiography

The subjects included in industrial radiography are listed below. The radiographer should be familiar with these subjects, all of which will be more fully treated in succeeding chapters.

(1) The source of radiation
- (a) The maximum energy of the source of radiation in Kev or Mev, including the energy spectral distribution
- (b) Emission rate of source in roentgens per curie per hour at one foot (r/c/hr at 1 ft. for gamma rays) (r/hr at 1 meter for X-rays)

(2) The specimen to be examined
- (a) Mass density of material (atomic number or chemical composition)
- (b) Thickness or length of absorption path

(3) The film to be used
- (a) Grain or the ability of the film to resolve images
- (b) Speed and relative exposure required to attain desired radiographic density
- (c) Film processing and interpretation

(4) Geometric principles
- (a) Size of source of radiation
- (b) Source to film distance
- (c) Specimen dimensions and shape
- (d) Specimen to film distance
- (e) Projected images (geometric enlargement and distortion)
- (f) Calculations

In addition to these outlined principles, every successful radiographer must know and practice these topics:

(1) Radiography techniques
- (a) Exposure calculations
- (b) Exposure arrangements

(2) Interpretation of radiographs

Chapter 9

Elements of Industrial Radiography*

9–1 Sources of Radiation

Industrial radiography makes use of X- and gamma radiation. This type of radiation is sometimes called "penetrating radiation" to distinguish it from other types of electromagnetic radiation such as light or radio waves. While X- and gamma radiation are very penetrating, the intensity of the radiation is changed by its passage through materials and defects in materials. This is the basis for its use in nondestructive testing.

9–1.1 *Production of X-rays.* When high speed electrons, which may be called "cathode rays," are suddenly slowed by striking matter, X-rays are produced. Equipment to produce X-rays must provide a source of electrons, a vacuum path along which the electrons may be accelerated, and a metal target. The X-ray tube supplies these requirements. In addition to the tube, there must be an electrical power source to heat the filament of the tube so it will give off electrons and a high voltage source to accelerate these electrons toward the metal target.

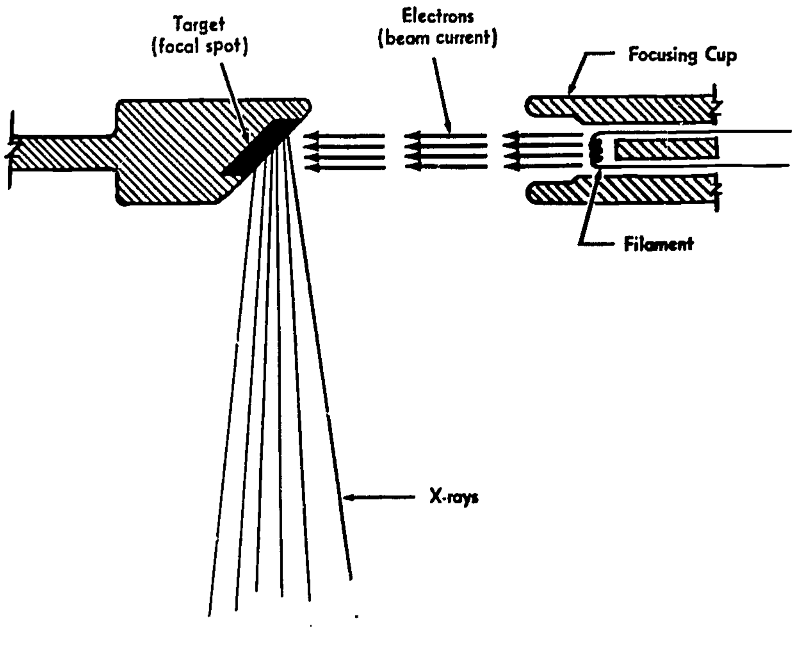


FIGURE 9.1.—Diagram of X-ray Tube.

The filament power source is a low voltage source which furnishes several amperes of current. This power source is usually a small transformer. The higher the temperature of the filament, the more electrons it emits. X-ray tubes have a focusing cup around the filament to help direct the emitted electrons toward the target. The small area of the target hit by the stream of electrons is called the focal spot. The stream of electrons from filament to target is the tube current and is measured in milliamperes.

The amount of tube current is controlled by regulating the heating current supplied to the filament. A rheostat in the primary circuit of the filament transformer is the usual control method. Much of the energy supplied to the X-ray tube is changed to heat at the focal spot on the target. In fact, in an X-ray tube with 300 kv applied to the target or anode, only about 3 percent of the electron energy is changed to X-rays. The remainder of the energy appears in the form of heat. Since the efficiency of the target material in producing X-rays is proportional to its atomic number, tungsten is most commonly used. It has both a high atomic number and a high melting point. Some tubes have a metal rod connected to the target which conducts the heat outside the tube to cooling fins. Other tubes have a hollow anode so that oil or water may be circulated to remove the heat. Still other tubes have a rotating anode which moves the target material so as to allow cooling.

X-ray machines are designed so that different voltages may be applied between filament and target to fit the differing needs which may arise. The higher the voltage, the greater the speed of the electrons to the target. High-speed electrons produce X-rays of shorter wavelength and higher penetrating energy than do low-speed electrons. The highest energy X-rays emit are determined by the highest voltage produced in the power transformer. X-ray machines for low-energy levels may have from 10,000 to 100,000 volts of tube voltage. The tube wall must be thick to withstand the stress created by the vacuum and this thick wall will absorb the low energy radiation. Special win-

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dows are provided to allow the "soft" X-rays to leave the tube itself.

The 400–kv X-ray machine is about the highest energy machine to use the single section tube. Such a machine produces X-rays with all the wavelengths produced by the low-voltage machines and also X-rays of a shorter wavelength and hence of a higher energy level. These high voltage machines are used to generate X-rays to penetrate thicker, heavier materials. Other types of X-ray generators are used for operation at one million volts and higher.

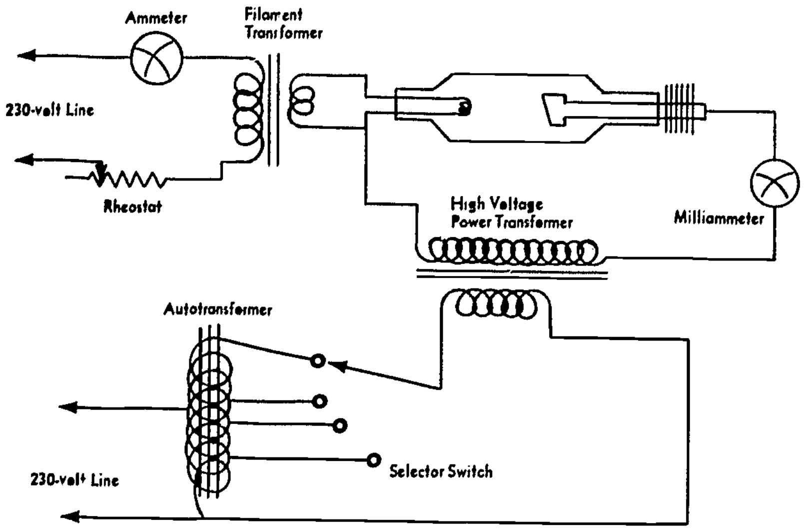


FIGURE 9.2.—Basic X-ray Circuit.

The basic X-ray circuit in Figure 9.2 shows a highly simplified diagram of a self-rectified circuit. Other basic circuits have rectifying tubes to supply the high positive voltage to the anode or target of the X-ray tube. In this circuit it may be seen that there are meters to measure the filament current and the tube current. Also, there are means of controlling or adjusting the filament current. There is an autotransformer selector switch to choose the high voltage to be applied to the anode or target. This allows an operator to choose low-energy X-rays or higher energy X-rays as needed. Actual X-ray circuits contain many other types of controls such as switches, timers, protectors, and contactors.

Characteristics of X-radiation. The energy of radiation is often expressed in terms of electron volts. Because this is a very small unit, kiloelectron volts (kev) and million electron volts (Mev) are the units most frequently used. It has been noted that as the wavelength of X-radiation becomes smaller, the energy level (also penetrating power) of the radiation becomes greater. (The radiographer will find other terms in the literature. Kilovolts, Kv, is the energy potential applied to the X-ray tube terminals. Kilovolts peak, Kvp, refers to the maximum, or peak, energy of the applied wave form.)

Radiation from an X-ray tube may be considered to consist of two parts. These are referred to as the continuous X-ray spectra and the characteristic X-ray spectra. Electrons in the beam impinging on the target material and some electrons ejected from the target atoms give up kinetic energy as they strike nuclei of target atoms. The loss of energy results in X-rays. Since these electrons have a wide range of velocities, the X-rays generated cover a wide band of wavelengths. The wavelength depends upon the energy given up by the electron. This provides a continuous spectrum of X-rays and is the radiation of most use in industrial radiography. Since the velocity of the impinging electrons depends upon tube voltage, a high tube voltage not only increases the intensity of all the continuous radiation but produces X-rays of shorter wavelength than does a low tube voltage.

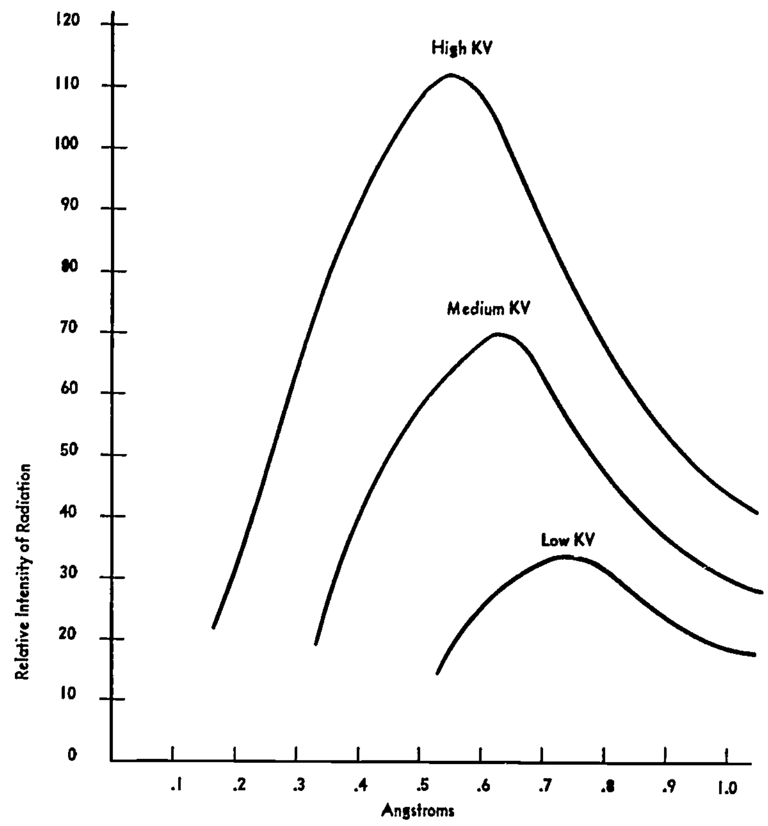


FIGURE 9.3.—Continuous X-ray Spectrum at Different Tube Voltages.

Some electrons in the beam traveling from filament to target strike and dislodge orbital electrons in atoms of the target material. The atom gains in energy by this action, but the orbital electron is soon replaced and the atom emits X-radiation of a "specific" wavelength characteristic of the element making up the target material. This material is frequently tungsten. Being of specific wavelengths this X-radiation does not cover a band of frequencies. The energy of the characteristic spectrum is small compared to that of the continuous spectrum.

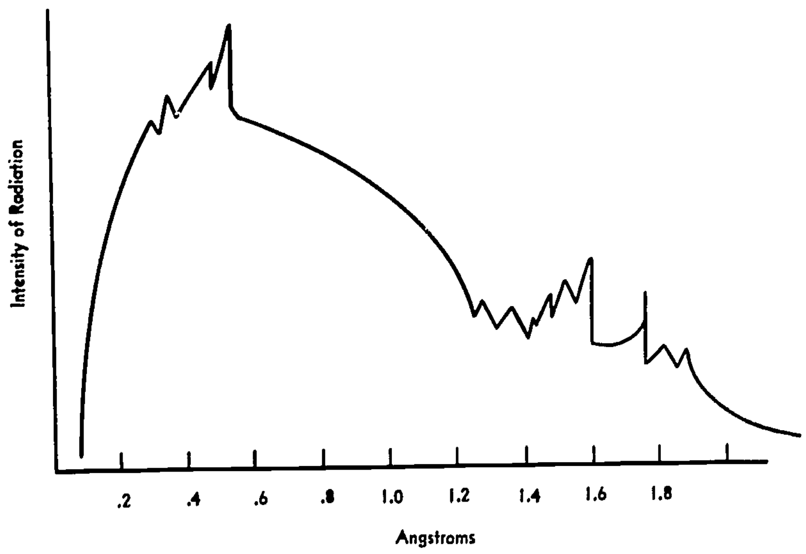


FIGURE 9.4.—Characteristic X-ray Spectrum of Tungsten.

A broad energy spectrum is sometimes undesirable since the low energies are more readily scattered and absorbed. To overcome this, filters are placed over the tube window. Figure 9.5 shows that low energy (long wavelength) X-rays are successively eliminated from the beam by addition of filters 1 mm (millimeter), 2 mm, and 3 mm thick.

Beyond 400,000 volts, a different sort of X-ray generator must be used. The single-section tube described here is not practical beyond this point. The resonance-transformer unit and the electro-static-belt generator are commonly used at the one and two million volt levels. Beyond these levels linear accelerators and betatrons have been used to generate X-radiation of extremely short wavelengths and high intensity.

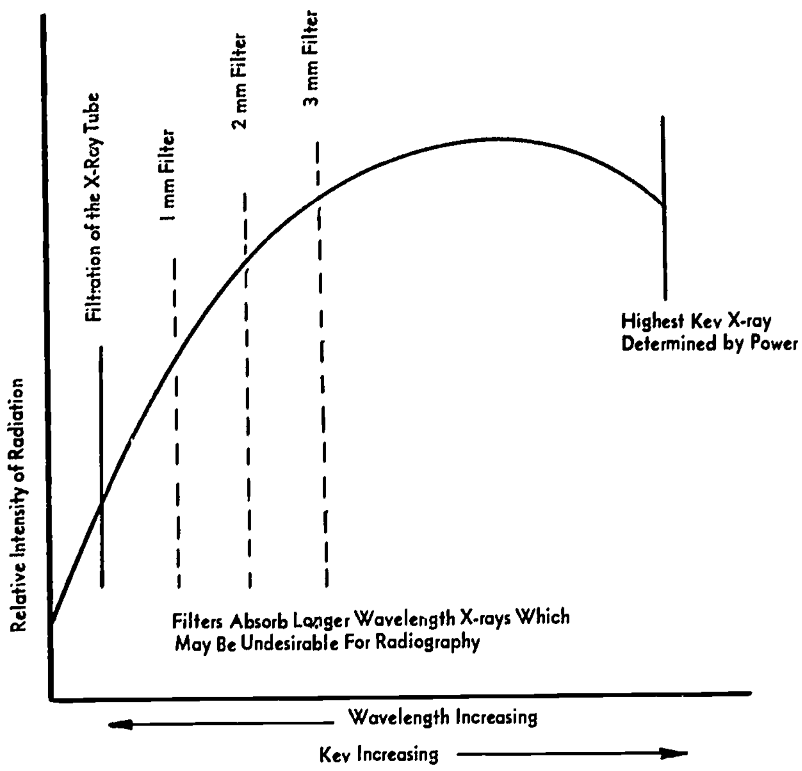


FIGURE 9.5.—Continuous X-ray Spectrum Showing High and Low Energy Limits.

9–1.2 *Sources of Gamma Rays.* Radioisotopes for gamma radiography are available from:

(1) Naturally occurring materials (radium–226)
(2) Fission products (cesium–137)
(3) Activation by neutron bombardment (cobalt–60, iridium–192, thulium–170, etc.)

Radium–226 is obtained by refining ores such as pitchblende and carnotite. It is commercially available as the chemical compounds radium bromide and radium sulphate.

Paragraph 3–4 and Figure 3.3 provide a brief explanation of how nuclear reactors produce fission products. Cesium–137 is one of the most abundant radioisotopes in the fission products. The cesium can be chemically separated from the other fission products. Since cesium

TABLE 9.1.—Characteristics of Gamma Radiography Sources.

Isotope	Symbol	Half-life	Gamma Energies Emitted, mev	Emissivity R/C Hr @ 1 ft.	Specific Activity C/gram
Radium–226	Ra–226	1,620 Years	2.20 to 0.24, 11 Principle Gammas	9.0	1
Cobalt–60	Co–60	5.3 Years	1.33 and 1.17	14.4	up to 150
Iridium–192	Cs–137	30 Years	0.66	4.2	up to 22
Cesium–137	Ir–192	75 Days	0.61 to 0.21, 12 Principle Gammas	5.9	up to 500
Thulium–170	Tm–170	120 Days	0.08 and 0.05		
Gadolinium–153	Gd–153	240 Days	0.10, 0.07, and 0.04		
Samarium–145	Sm–145	240 Days	0.06 and 0.04		

is extremely active chemically in its elemental form, it would be most difficult to handle. For this reason cesium–137 sources are available as the compound, cesium chloride.

All other gamma emitting radioisotopes now being used for industrial radiography are produced by neutron activation as described in paragraph 3–5. Table 9.1 lists properties of gamma sources useful for industrial radiography.

9–1.2a *Encapsulation of Radioisotopes.* In gamma radiography the energy emitted from decaying nuclei is used as described in Chapter 8. The radiography equipment must be designed to permit the gamma rays to escape, *but* it is mandatory that the radioactive chemicals (metals or compounds) be contained and not released into the environment where the chemicals could contact or enter the human body. This containment is accomplished by *sealing* the radioactive materials in capsules—a process called "encapsulation." Encapsulation is a highly specialized process requiring the most careful (1) design, (2) fabrication, and (3) quality control to assure integrity of the entire process.

Selection of materials and designs for capsules must be based upon these criteria:

(1) Resistance to corrosion of the radioactive material
(2) Damage to capsule material caused by the emitted radiation
(3) Resistance to corrosion from the environment in which the capsule is to be used
(4) Resistance to high or low temperature regions in which the capsule is to be used
(5) Resistance to erosion or abrasion
(6) Structural stresses including impact, vibration, creep, and fatigue loading
(7) Sealing technique, e.g., screws, resins or cements, crimping, soldering, silver brazing, shielded arc welding, electron beam welding, cold welding

Items 1 through 6 are deemed self-explanatory with the additional statement that the wall thickness should be as thin as practical designs allow since this will minimize radiation absorption by the walls of the capsule.

Item 7, sealing, is most important since release of contamination and containment of the radioactive material are dependent upon the sealing design and fabrication. (Careful leak testing, described later, is required to assure that the sealing has been properly accomplished and continuously maintained.)

Early capsule designs used screws, cements, crimping, and soldering techniques which *did not* adequately serve the industrial gamma radiography source requirements. An evolutionary process has replaced these with better capsules and seals. While several types of seals may be proved acceptable, it is certainly true that fusion welding, properly done, will produce the desired quality. (Figures 9.6 and 9.7)

Metallic sources of cobalt, iridium, and thulium are more easily contained than compounds of material such as cesium. Several unfortunate incidents have occurred with leaking cesium sources in industrial operations. For this reason the cesium sources are usually "double encapsulated." This means that the cesium capsule, after fabrication and leak testing, is placed into and sealed in a second capsule which is also leak tested. Field experience of this capsule design has proved so satisfactory that many sources, including metallic materials, are now made by the double encapsulation technique. (Figure 9.8)

Many source designs have been prepared for special conditions or equipment. There is no doubt that others will be produced as equipment and techniques are developed. The radiographer should carefully evaluate sealed sources with respect to his service requirements and the design criteria listed above.

9–1.2b *Leak Testing Sealed Sources.* After a capsule is sealed, a test is required to determine if the closure is complete. If the sealing is not properly done, the by-product material will escape and contaminate other equipment and the working area. After leak testing, the source exterior surfaces must be decontaminated to the degree that no more than 0.005 microcuries of removable contamination is present.

9–1.2c *Characteristics of Gamma Radiography Sources.* Radioisotopes for industrial radiography have discrete energies emitted compared to continuous energy spectra produced by X-ray machines. The thickness of the specimen

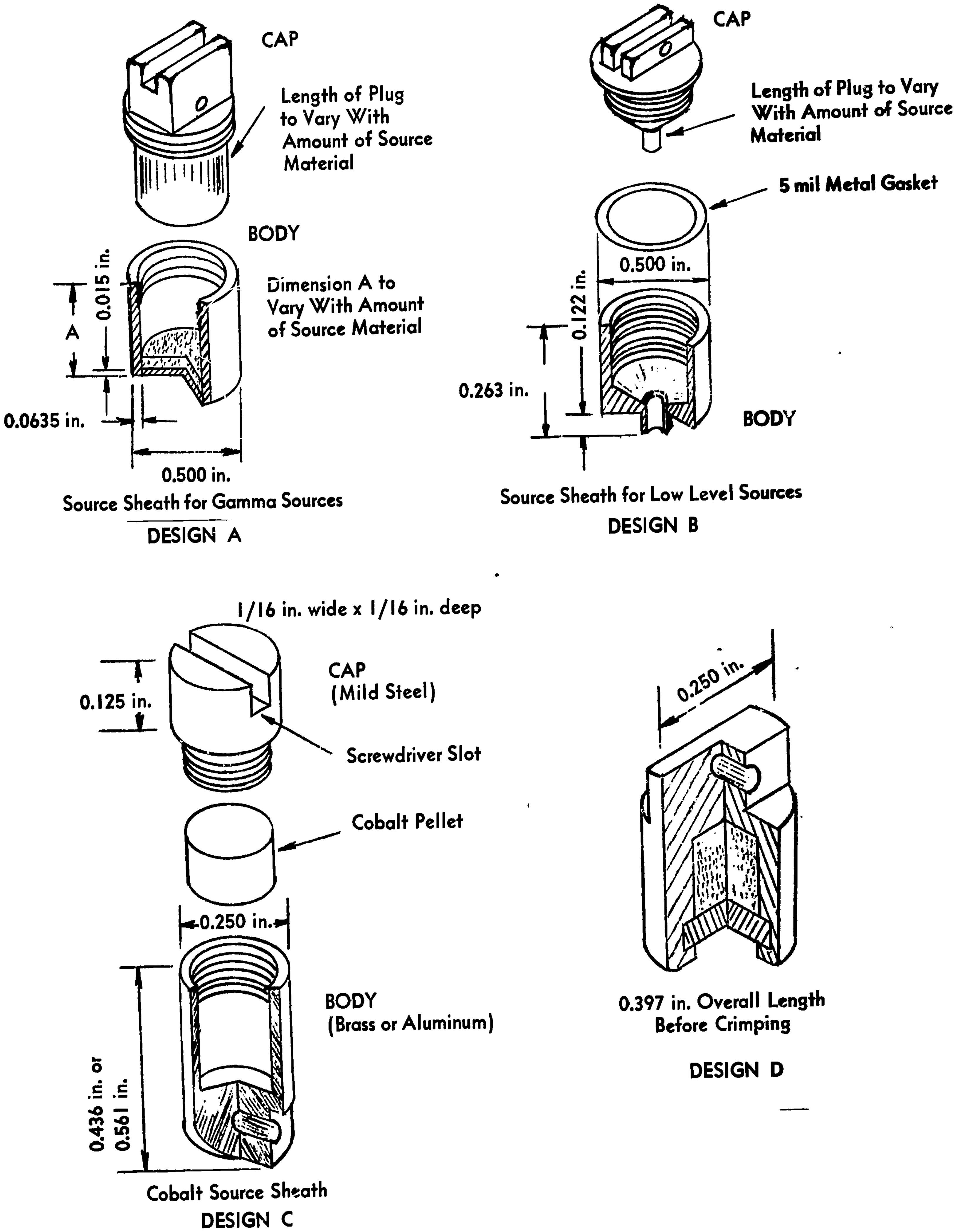


Figure 9.6.—Early Capsule Designs.

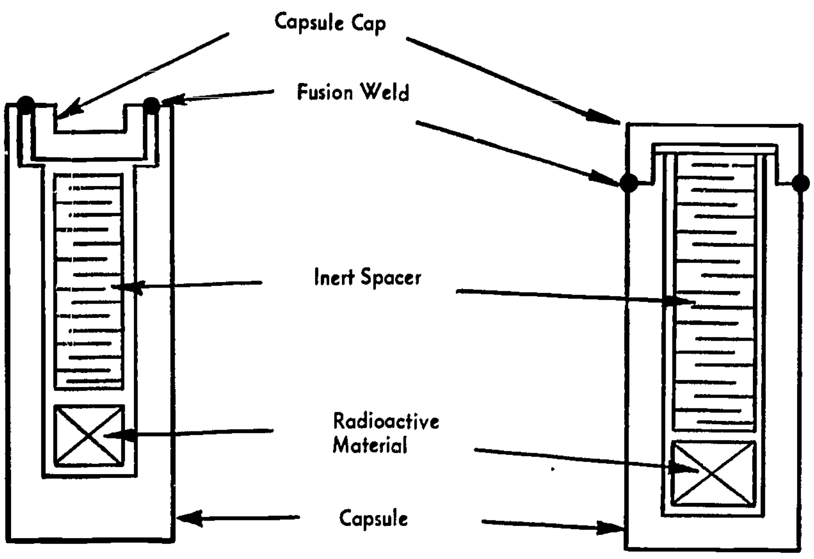


FIGURE 9.7.—Fusion Welded Capsule Designs.

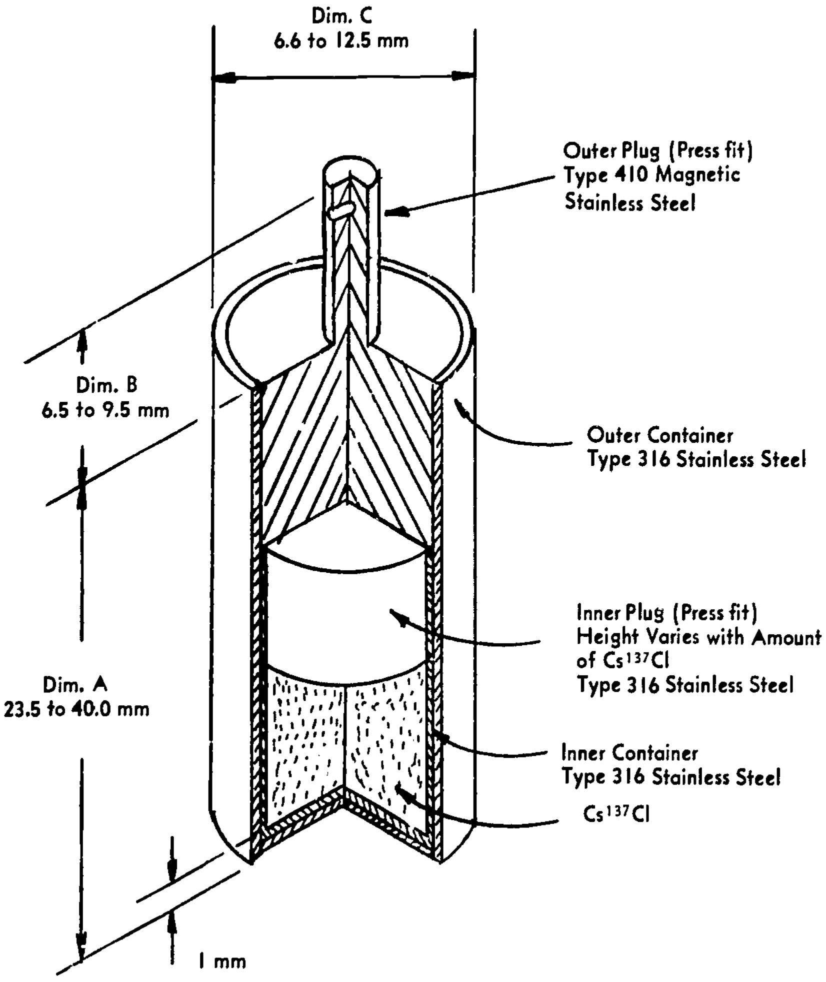


FIGURE 9.8.—Double Encapsulation.

will determine the energy intensity required for penetration and film exposure. Isotopes used for radiography are listed in Table 9.1.

In selecting a radioisotope for a particular class of work the desired characteristics would be (1) appropriate energy (mev), (2) high specific activity which would give small source size and high emissivity, and (3) long half-life. Since half-life and mev emitted are physical constants for each isotope, there is no control by the radiographer. He can only select the isotope having the energy (mev) required to penetrate the specimen. With respect to emissivity there is some degree of selectivity. Source manufacturers, upon request, will provide information on the available specific activity, total activity, source dimensions, and capsule designs.

Metallic pellets activated for radiography sources are usually available in the shape of right circular cylinders with dimensions as shown in Table 9.2. One or more pellets may be sealed in a single capsule to make a gamma ray source.

TABLE 9.2.—Metallic Pellet Dimensions.

Diameter	Length
1 millimeter	1 millimeter
1/16 inch	1/16 inch
1/8 inch	1/8 inch
1 centimeter	1 centimeter

9–2 Geometric Principles

Both X-rays and gamma rays obey the laws of light. Since a radiograph is a shadow picture of an object placed in a radiation beam, the common geometrical principles related to optics apply to the making of a radiograph. Major *differences* include the facts that (1) all objects are more or less transparent to radiation and (2) scattering of radiation presents problems not found in optics or photography.

9–2.1 *General Considerations.* Since radiation beams used in radiography behave much like light beams, they form shadows of objects much as does light. If an object is placed between a source of radiation and a piece of film, then a shadow will be cast on the piece of film (see Figure 9.9). Notice that the shadow is somewhat enlarged because the object is not in contact with the film and an orthographic projection is obtained. The amount of enlargement will depend upon the relative distances of the object from the film and from the source of radiation. If the object is lying on the film, there will be little or no enlargement. In fact the ratio of the diameter of the object (D_o) to the diameter of its shadow (D_f) is equal to the ratio of the distance from the source to the object (d_o) to the distance from the source of the film (d_s).

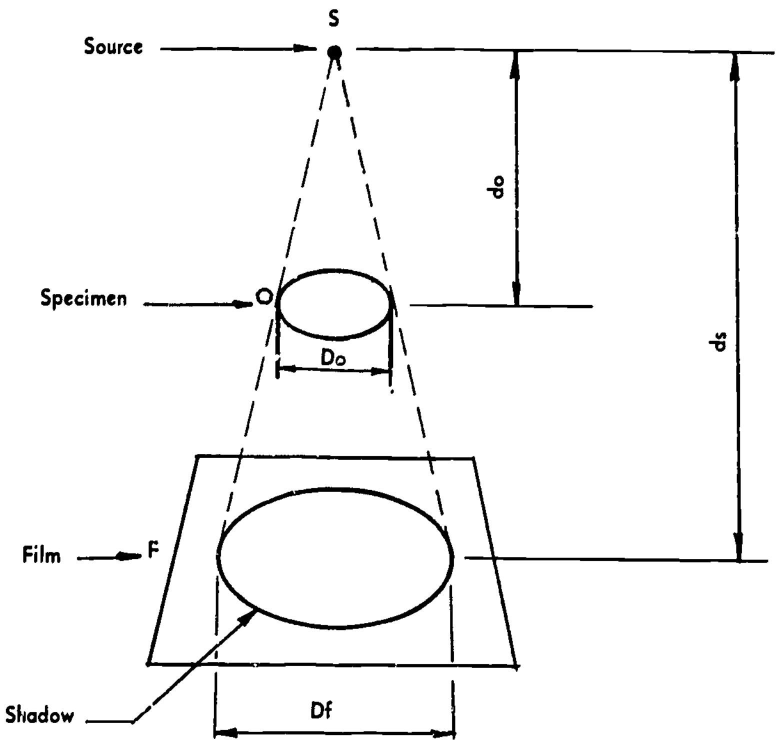
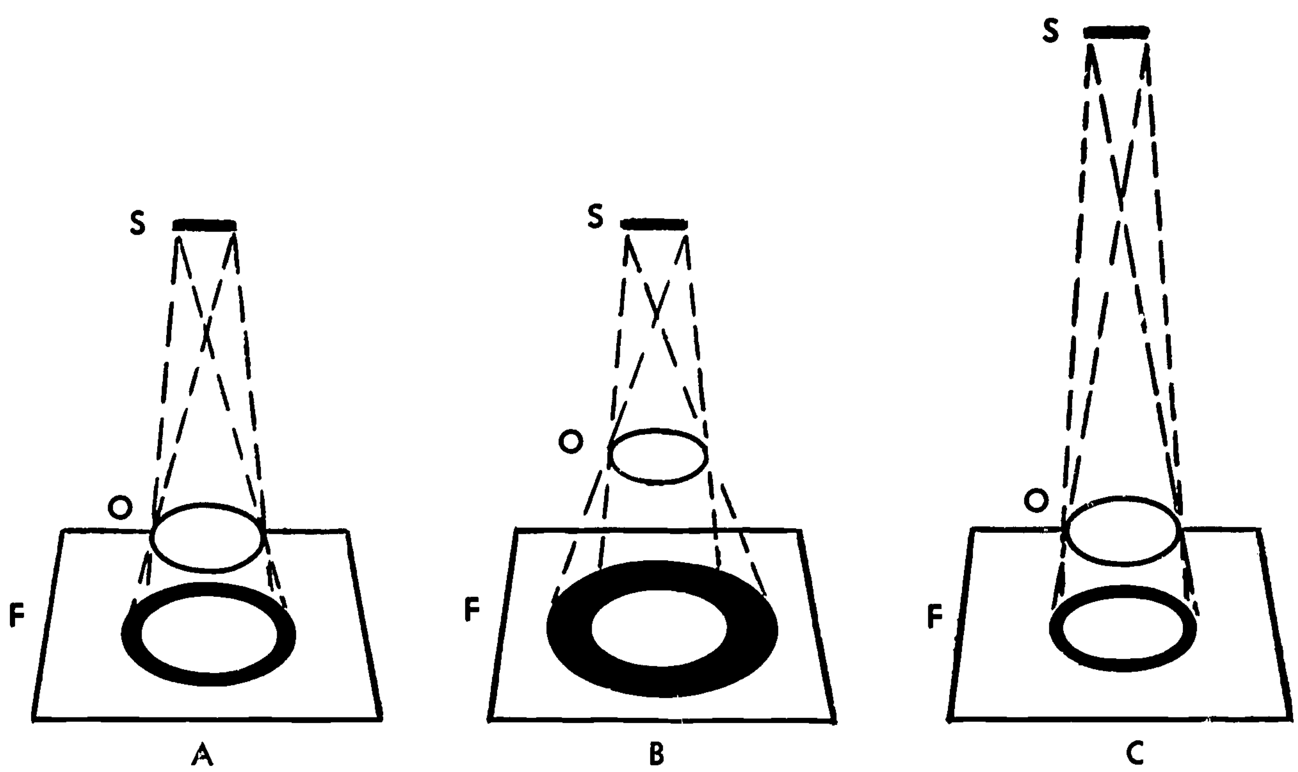


FIGURE 9.9.—Shadow Formation.

If a shadow the same size as the object is desired then (1) the object should be placed close to the film and (2) the source of radiation should be as far from the film as possible. The latter factor, of course, will be governed by the intensity of the source of radiation and the time which may be allowed for making the radiograph.

9–2.2 *Sharpness of Shadows.* The sharpness of a shadow depends upon the size of the source of radiation and upon the ratio of the source to object distance and the object to film distance. If the source of radiation has a definite area then the shadows cast by the source are not perfectly sharp. Each point of the source may be considered as casting its own shadow (see Figure 9.10). These shadows overlap and produce a fuzzy image or shadow. Notice that there is a fairly dark shadow surrounded by an ill-defined shadow. The ill-defined part of the total shadow is called the "penumbral" shadow. The penumbral shadow is also referred to as "geometrical unsharpness."

In order to minimize geometrical unsharpness, the specimen being radiographed should be as close to the film as possible and the source of radiation should be as far from the film as is practical (see Figure 9.10).



1. Sketch A shows a small geometrical unsharpness (penumbra) when the object "O" is close to the film "F."
2. Sketch B shows much larger geometrical unsharpness when the source to film distance is the same as in sketch A but the object to film distance is greater.
3. In sketch C, the object to film distance is the same as in sketch A but the source to film distance is larger than in sketch A. The result is a smaller geometrical unsharpness in sketch C.

FIGURE 9.10.—Geometrical Unsharpness, the Penumbral Shadow.

The amount of unsharpness or fuzziness in a radiograph may be calculated. In Figure 9.11, note that the triangle whose base is *F* (the source size) and whose apex is *A* is similar to the small triangle whose base is *U* and whose apex is *A*. Also note that *d* is the altitude of the larger triangle and *t* is the altitude of the smaller triangle. Therefore:

$$\frac{F}{U} = \frac{d}{t}$$

or

$$U = \frac{F \times t}{d}$$

where

U = the amount of geometrical unsharpness
d = the source to object distance
t = the object to film distance
F = the physical size of source of radiation

It has been reported that geometrical unsharpness as large as 0.01 inch may be acceptable on radiographs.

F, the source size, is beyond the radiographer's control (except on some double focus X-ray machines) after the source is manufactured. Smaller source sizes are desirable

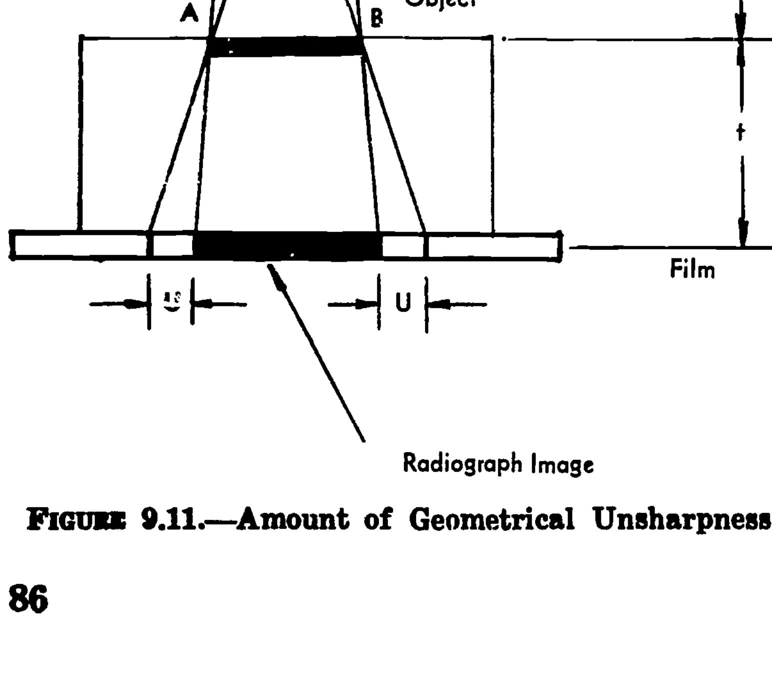


FIGURE 9.11.—Amount of Geometrical Unsharpness.

since they will produce radiographs having less geometrical unsharpness.

In practice, the radiographer controls the d/t ratio when selecting his exposure technique. The specimen thickness may be taken as "t" or object to film distance. A rule of thumb is that the d/t ratio should be 8 or more. The larger the ratio the better the definition on a radiograph.

9–2.3 *Distortion of Shadows.* Object images on film may be distorted for several reasons. The plane of the object and the plane of the film may not be parallel. The radiation beam may not be directed perpendicularly to the surface of the film.

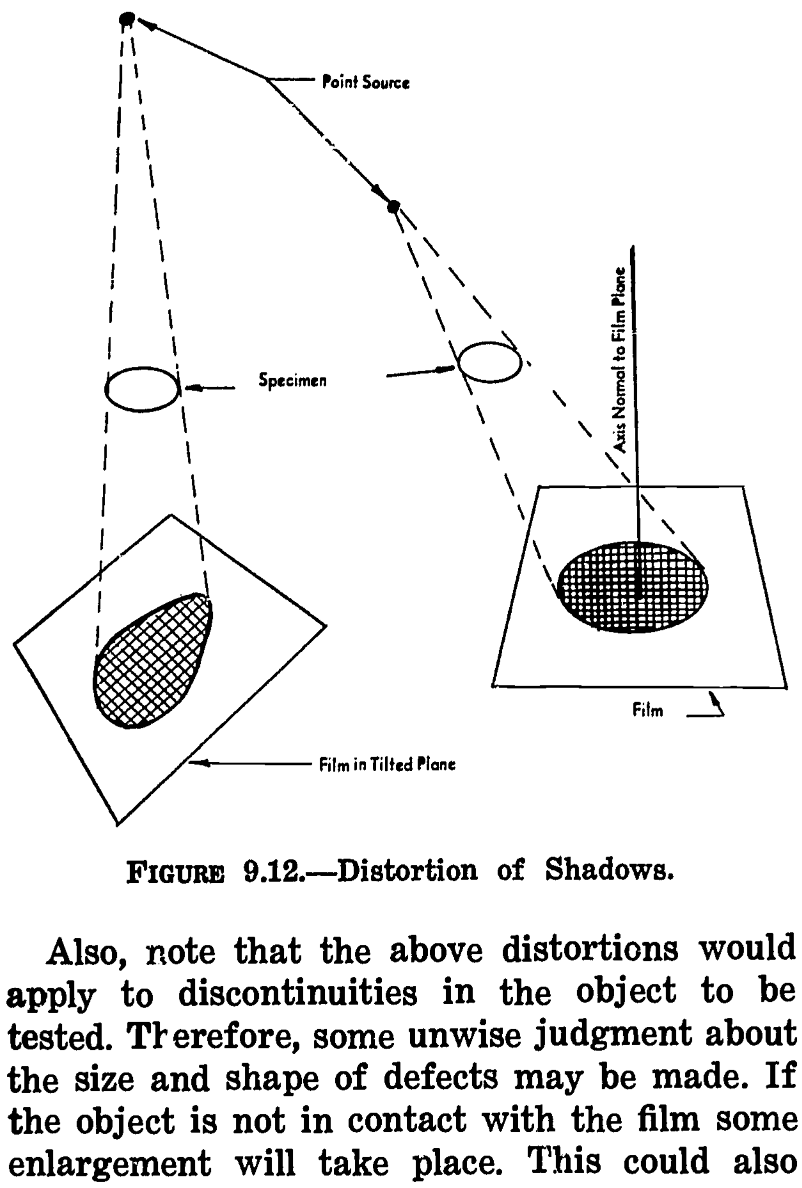


FIGURE 9.12.—Distortion of Shadows.

Also, note that the above distortions would apply to discontinuities in the object to be tested. Therefore, some unwise judgment about the size and shape of defects may be made. If the object is not in contact with the film some enlargement will take place. This could also cause some misjudgment about the size of the defect. In thick objects, there will be enlargement of images resulting from discontinuities which are not near the film.

9–2.4 *Enlargement.* Usually it is desirable to have the specimen and film as close together as possible in order to cut down geometrical un-

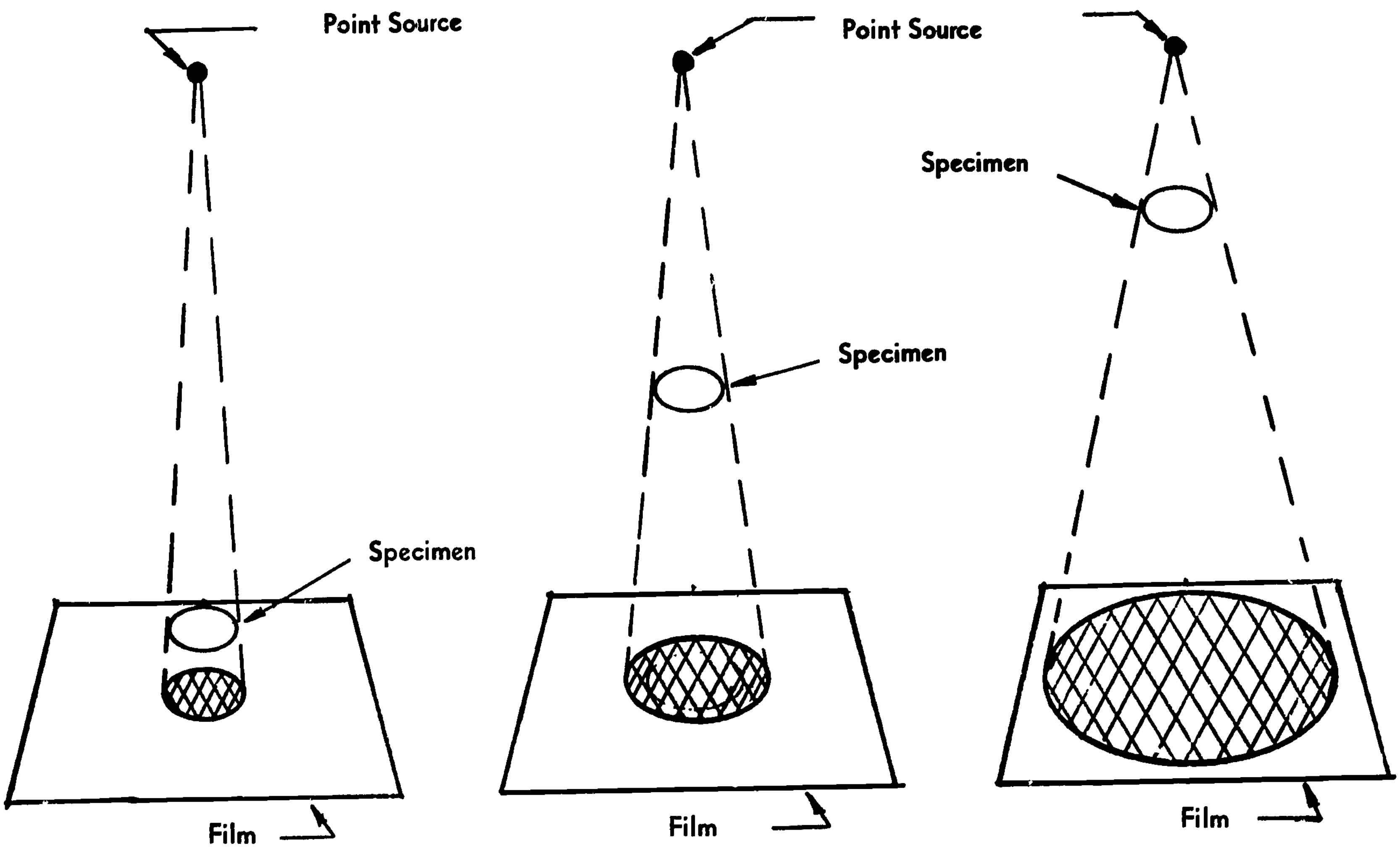


FIGURE 9.13.—Shadow Formation Showing Enlargement of Image.

sharpness. When the source of radiation is very small (a fraction of a millimeter) this is not too important. With an extremely small source of radiation the film may be placed some distance from the specimen. This will cause an enlarged image on the film without too much geometric unsharpness. Enlargements up to three diameters may reveal small defects not noticeable on regular radiographs. Microradiography, using extremely small sources of radiation, has produced enlargements of 20 to 30 diameters.

Geometric enlargement has the added advantage of decreasing the amount of scattered radiation reaching the film. The useful image formed on the film is the result of the direct beam of radiation. Scattered radiation reduces the sharpness and quality of the image.

Acceptable geometric enlargement can be attained only if the source size is very small.

9–2.5 *Summary*. Geometric principles of shadow formation applied to radiography are the bases for the following:

(1) The radiation source should be as small as possible. Definition in a radiograph is closely related to the physical size of the source of radiation.

(2) The distance from the source of radiation to the film should be as great as is practical.

(3) The film should be as close to the specimen as possible. Usually, the cassette or film holder should be in contact with the specimen.

(4) The center ray of the radiation beam should be perpendicular to the film. This will minimize distortion of the specimen image and of flaws or defects within the image.

(5) The plane of maximum interest on the specimen should be parallel to the film.

9–3 Specimen

Specimens radiographed in industry vary from thin low density plastics to thick high density metallic sections. Radiation interaction with and transmission through the specimen depend upon the radiation energy (Mev), specimen atomic number, and density. Review of absorption coefficients in Figure 4.7 indicates that:

(1) For a selected material, radiation penetrates more easily as the energy (Mev) increases.

(2) For a selected energy (Mev), the radiation penetrates more easily as the material density (atomic number) decreases.

Using these coefficients in the absorption equation discussed in paragraph 4–6, it is determined that for a selected energy and subject density, the amount of radiation transmitted is dependent upon the subject thickness and atomic number. Thicker sections absorb more and therefore transmit less energy. The converse is true of thin sections. Interrelations of radiation energy, specimen density, and specimen thickness are important in determining radiography exposure techniques (see Figures 11.1 and 11.2 and paragraph 11–2).

These conditions suggest that high energy radiation should be used to radiograph thick dense specimens. Alternately, low energy radiation should be used to radiograph thin low density subjects.

Radiographic contrast (see paragraph 10–2) is partially dependent upon subject contrast (see paragraph 10–3).

As radiation interacts with the specimen there will be long wavelength scattered energy that may reach the film. This will decrease overall radiographic contrast.

9–4 Radiation Scattering

Radiation scattering occurs in radiography with both X-rays and gamma rays. When a beam of either X-rays or gamma rays strikes an object, some of the radiation passes through the object, and some is absorbed by it. Also, some rays are scattered randomly as to direction. These scattered rays have longer wavelength and so are less penetrating than the primary rays. The film receives some of this scattered radiation which will cause it to fog. This serves to reduce the contrast on the film or parts of it and may result in a poor image of the object being radiographed.

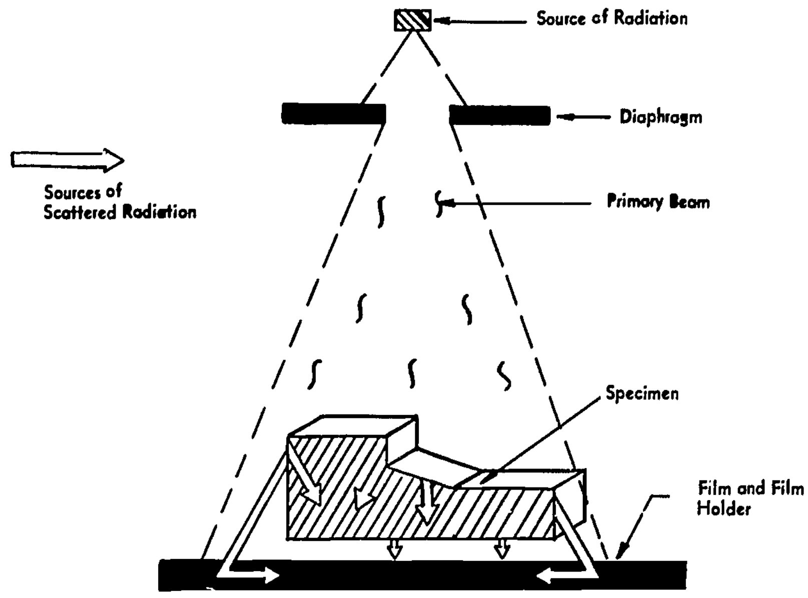


FIGURE 9.14.—Sources of Scattered Radiation.

Scattered radiation may come from any material in the path of the primary radiation. For example, the specimen, film holder, floor, walls, or other objects receiving primary radiation may be a source of scattered radiation. When thick materials are radiographed, more scattered radiation may reach the film than primary radiation. Unless this scattered radiation can be controlled or prevented from reaching the film, the radiographic image may be of very poor quality.

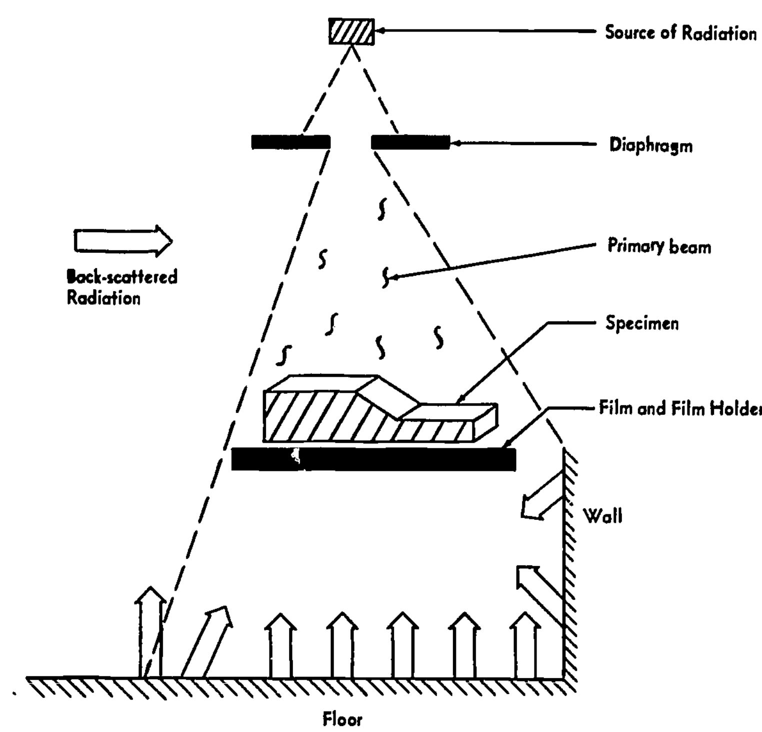


FIGURE 9.15.—Back Scatter From Floor, Walls, or Objects.

9–4.1 *Types of Scatter.* Generally, most scattered radiation reaching the film comes from the specimen being radiographed. This would be called *forward scatter.* Scattered radiation seriously affects the edge of the image on the film. The result is an image with hazy or foggy edges. Also, any portion of the film holder that extends beyond the specimen may receive primary radiation and so cause scattering which affects the edges of the specimen image. Such scatter as this causes the condition known as *undercut.*

When primary radiation reaches objects beyond the specimen being radiographed, *backscattered* radiation occurs. Such scattered radiation may come from the floor, walls, or table top on which the specimen and film holder are placed. (Figure 9.15)

Chapter 10

Radiographic Film*

10–1 Introduction

Film is a prime essential for radiography work. While the general make-up of the film itself is relatively simple, its behavior characteristics are much more complicated. The latter are of concern to the radiographer, since the success and quality of his work will depend on his knowledge and correct use of films which are manufactured with many different properties.

An industrial radiographic film is a thin, transparent, flexible plastic base which has been coated with gelatin containing microscopic crystals of silver bromide. Some film have one side and some have both sides of the base coated with a layer, approximately 0.001 inch thick, of this gelatin and crystals. The gelatin and crystal mixture is called an *emulsion.*

This discussion is concerned with what has been termed the "sensitometric characteristics" of radiography film. Said another way, this section presents the properties of film which determine the exposure time required to produce an image of a desired density on the film after chemical processing and the film's ability to reveal structural details in the specimen.

The human eye is the actual detector of the radiography process. The eye observes areas of the radiograph depending upon the amount of light passing through dark gray areas (described as having high density), compared to the amount of light passing through light gray areas (low density) (see Figure 10.1). *Contrast* is a comparison of the light to dark gray areas. If the radiograph has a large difference in density, the radiograph has high contrast. If the radiograph has small density differences, the radiograph has low contrast. The eye usually more easily discerns high contrast areas, but this can depend upon the "radiograph image sharpness," called *definition.* If the density change is clearly outlined, the radiograph has good definition and is readily seen by the eye.

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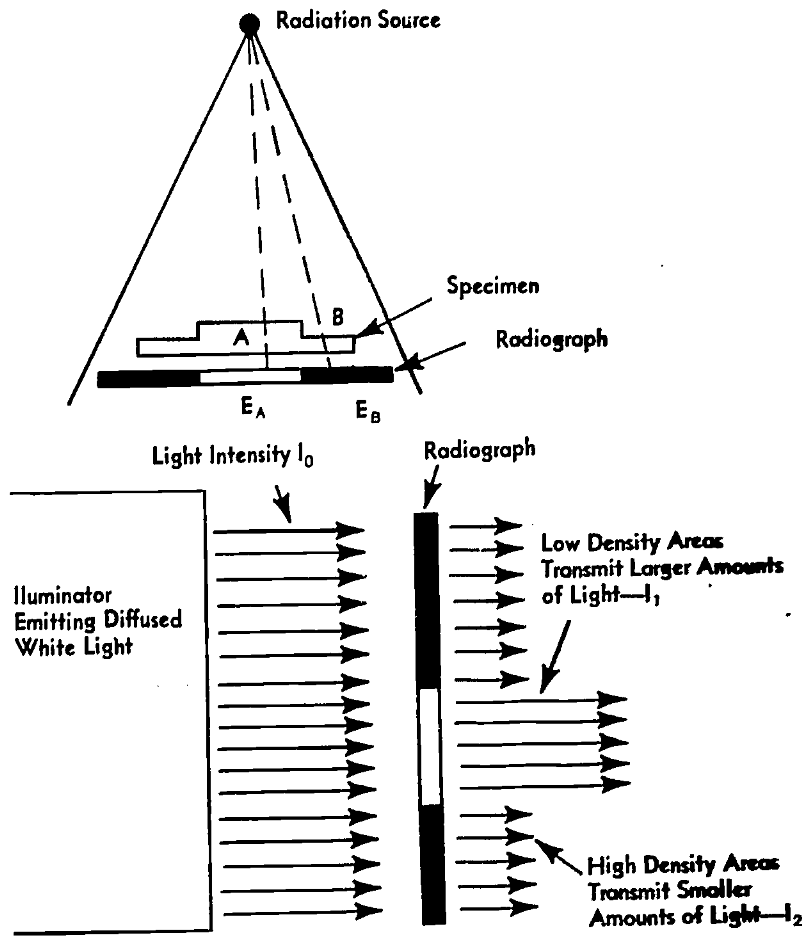


FIGURE 10.1.—Film Density.

Sometimes a high contrast radiograph will have gradual shading of the gray areas and the eye will not readily observe the image. Knowledge of terms and characteristics related to films is necessary to understand how energy passing through a specimen can be resolved into images that can be "read" by the eye and interpreted as identifiable discontinuities in the specimen.

10–2 Radiographic Contrast

A combination of subject contrast and film contrast determines *radiographic contrast,* which is defined as a comparison of densities on developed film areas. Usually, finer details can be observed with greater contrasts; however, loss of detail visibility may occur in the extreme high and low density areas.

Radiographic contrast resulting from a given set of conditions will depend upon:

A. Subject Contrast

(1) X-ray kilovoltage or isotope gamma

ray energy

(2) Scattered radiation

B. Film Contrast

(1) Screen type
(2) Film contrast characteristics
(3) Film density as determined by:
   (a) *Exposure* (defined as radiation intensity multiplied by the exposure time)
   (b) Chemical processing

10–3 Subject Contrast

Beginning with the fact that the radiation passes through a specimen depending upon the (1) specimen (subject) density, (2) specimen thickness, (3) specimen atomic number, and (4) radiation quality (energy spectrum), it is apparent that different amounts of radiation will pass through a solid area compared to a porous area of the specimen. The ratio of radiation intensities passing through two selected portions of a specimen is called *subject contrast*. Specimens having uniform thickness and composition have very low subject contrast. The opposite is true if the specimen has large thickness changes.

Subject contrast varies according to the energy of the radiation and specimen density thickness and atomic number (see paragraph 4–6 and Table 4.2). Careful consideration of energy absorption indicates that subject contrast can be increased by lowering X-ray kilovoltage or using Ir–192 instead of Co–60 sources, i.e., lowering the gamma ray Mev.

10–4 Film Contrast, H & D Curve

Film emulsion can be manufactured to give different film contrasts as well as other properties such as speed and graininess. Radiographic sensitivity is dependent upon the ability of film to detect and record varying radiation exposures as density changes. These density changes, film contrast, are best described by the characteristic curve, Figure 10.2, often called the H & D curve. This relates film density to the logarithm of the radiation exposure.

Exposure of a film is defined as the product of the radiation intensity, I, reaching the film and the radiation exposure time, t.

$$E = I \times t$$

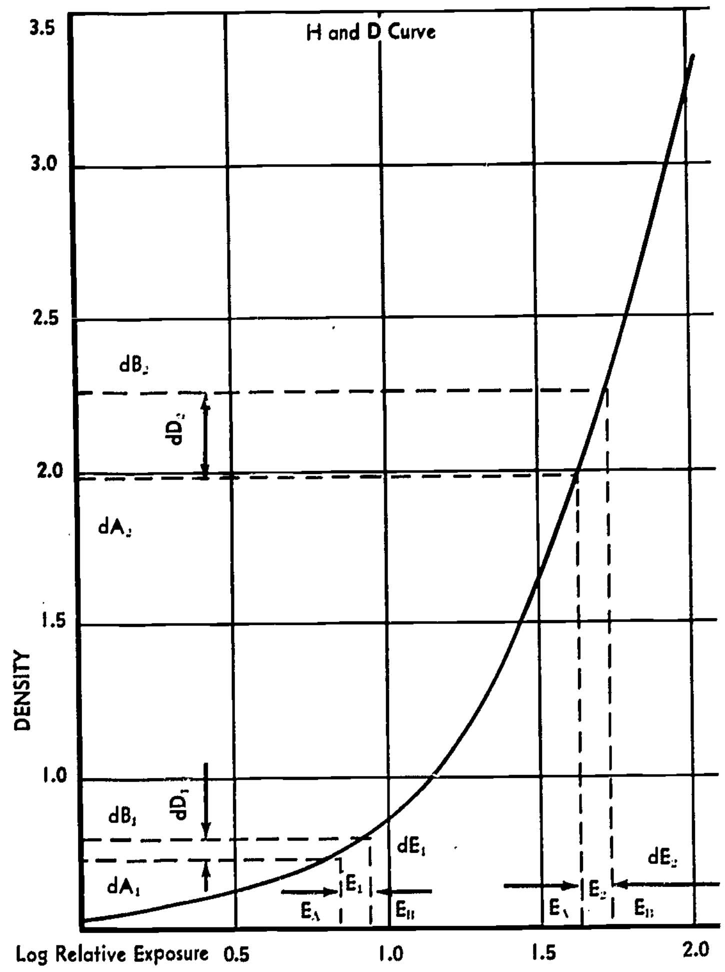


FIGURE 10.2.—Film Characteristic Curve.

For convenience, this is expressed as the base 10 logarithm of E for plotting the H & D curve.

Film density, more correctly called the film optical density, is defined mathematically,

$$D = \log_{10} \frac{I}{I_o}$$

where

D	=	film density
I	=	intensity of light incident upon a film
I_o	=	intensity of light transmitted through a film
$\log_{10}$	=	base 10 logarithm

The eye can more readily interpret large density differences, or contrast. In fact, there is a lower limit of contrast that cannot be observed by the naked eye. H & D curves have contours that increase contrast as the exposure increases and the overall film density increases. On referring to Figures 10.1 and 10.2, it can be seen that film exposure E_A at radiation path A is less than the exposure E_B at radiation path B. For a low exposure E_1, the result is that film density dA_1 will be less than film density dB_1. The difference in film density $dD_1 = dB_1 - dA_1$. In the low density portion of the H & D curve, i.e., density less than 1.0, the low contrast dD_1 will probably not be discernible by the eye.

To improve the radiographic technique, the exposure could be increased to E_2. It is very evident on Figure 10.2 that the density difference dD_2 is greater than dD_1 and the darker film could be easily read by the human eye. Generally, the contrast of industrial radiography films increases continuously as the overall film density increases. Good industrial radiographs should not be exposed for density less than 1.5, and the high density is limited only by the light intensity of the illuminator.

Figure 10.3 shows H & D curves for 3 different films. Each has a different speed and a somewhat different film contrast. Higher speed films are the curves toward the left on the log E axis. *Speed* is defined as the relative exposure required to attain a desired density. Film contrast is determined by the shape of the H & D curve.

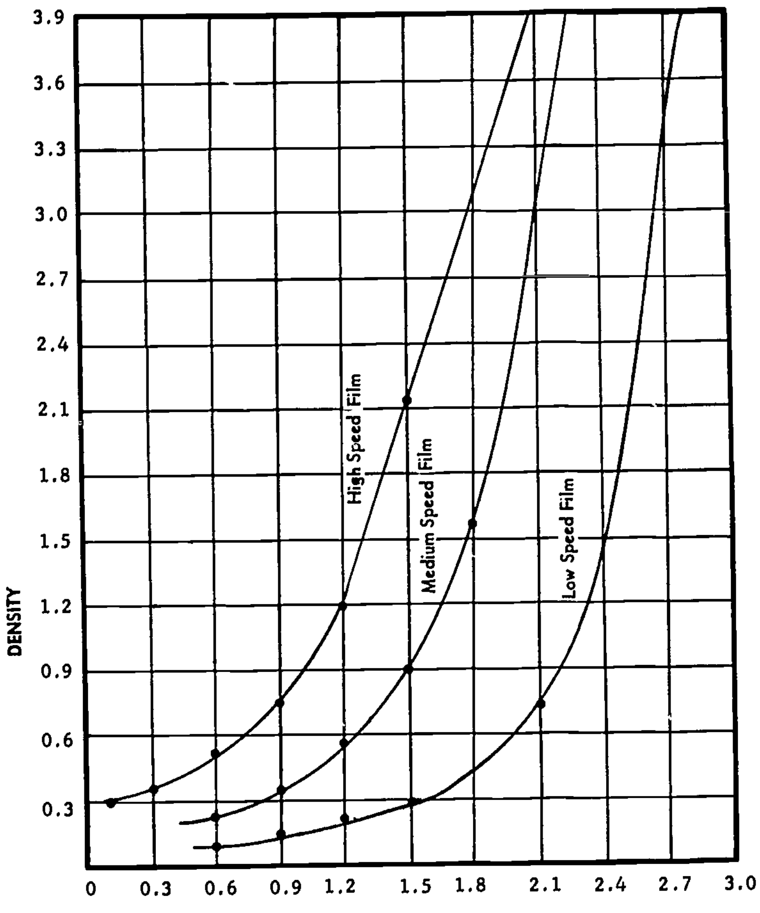


FIGURE 10.3.—Relative Film Speed.

The shape of the H & D curve and its position along the log E axis, depend, primarily, upon its design and manufacture. However, the curve's position along the log E axis depends, to some degree, upon developing (see paragraph 10–6). Radiation quality has very little affect upon the shape of the H & D curve.

10–4.1 *Speed.* Mathematically stated, the speed is inversely proportional to the exposure required to attain a desired density. This means that a high speed (fast) film requires a low exposure, while a slow speed film requires a long exposure to reach the same density.

Film speeds, Figure 10.3, are indicated by the position of H & D curves along the log E axis. The faster films are located toward the left and the slower ones to the right. Radiation quality partially determines the curve position on the log E axis. Film processing, paragraph 10–6, affects the curve's position.

10–4.2 *Graininess.* Film images are formed by multitudes of microscopic silver crystals, called grains. Groups of grains are visible to the eye, producing an overall condition described as *graininess.* All films have this condition. Some have large grains (high graininess) and some have fine grains (low graininess).

Graininess is somewhat related to radiation energy, although the relation is not clearly defined. It is also directly related to the degree of development (longer developing time increases graininess), which in turn is governed by time, temperature, and the degree of exhaustion of the developer.

Graininess is affected by screen type. Fluorescent screens increase grain size as energy increases. This condition prevents use of fluorescent screens at high energies. Lead foil screens have a very slight effect on graininess at any X- or gamma ray energies. For this reason they are superior to fluorescent screens at higher energies.

Graininess is one of the factors which determines the detail that can be perceived on a film. A relative comparison can be made by visualizing photographs in a newspaper compared to a slick paper magazine. The newspaper photo is composed of large dots, widely spaced, and there is poor resolution of detail. This is comparable to high graininess film. In slick paper magazines, photos are composed of small dots, closely spaced, and there is good detail resolution. This is comparable to low graininess film. Desirable fine resolution suggests that low graininess film should be used for determining small specimen discontinuities.

10–4.3 *Film Contrast, Speed, and Graininess.* In non-destructive testing, the radiograph must be of acceptable quality to resolve the specimen discontinuities which are likely to prevent the specimen from performing its desired service. Film contrast, speed, and graininess are interrelated so the radiographer must select films that can develop the desired contrast and image sharpness, which depend upon graininess. Of course, it is desirable to make the exposure in the shortest time.

Unfortunately, the fast films do not have the better contrast and graininess properties. Generally, fast films have large grain and poor resolution, while slow films have fine grain and good resolution. Practical aspects of these contrasting properties will be discussed in Chapter 11.

10–5 Radiographic Screens

Researchers made the discovery many years ago that when an X-ray or gamma-ray beam strikes a film, it is seldom that more than 1 percent of the energy is absorbed. This high loss of available energy presented a problem because the formation of a radiographic image is primarily governed by absorbed radiation. After experimentation with various methods of more fully utilizing the energy wasted in the radiography process, two types of radiographic screens—lead foil and fluorescent—were developed. These screens were designed so as to improve radiographic techniques without unduly complicating the radiography process.

The primary function of a radiographic screen is to intensify the photographic action of radiation on the film and thus to reduce time and other exposure factors. Lead foil screens perform additional functions of reducing the effect of scattered radiation, including back scatter, as well. Fluorescent and lead screens are described in some detail below.

10–5.1 *Lead Foil Screens.* The advantages of lead screens are such that they are essential in practically all radiography with gamma rays and some radiography with X-rays. Their function of removing scattered radiation is equally as important as their intensifying action. The latter reason is why they are recommended for use even in some cases (for X-ray) where they exhibit no intensifying action.

Lead foil screens are commonly used on both sides of the film in industrial radiography so as to improve quality. In radiography with gamma rays the front lead foil need be only 0.004 to 0.006 inch thick, a thickness insufficient to seriously absorb the primary radiation beam. The back screen should be somewhat thicker to reduce back-scattered radiation. Such screens should be selected with extreme care. Although commercially pure lead is satisfactory, an alloy of 6 percent antimony and 94 percent lead is harder and stiffer and has better resistance to wear and abrasion. Tin coated lead should be avoided under all circumstances, since irregularities in the tin cause a variation in the intensifying factor of the screen. Minor blemishes do not affect the screen appreciably but large blisters or cavities do.

The intensifying action of a lead foil screen is caused by the electrons emitted under gamma-ray (or X-ray) excitation. This explains why the surfaces of screens must be kept free of grease and lint, as they will produce light marks on the radiograph because of their high electron absorption. Grease and lint may be removed from lead foil screens with a solvent, such as carbon tetrachloride, or may be gently rubbed with a high grade of steel wool. The shallow scratches left by the steel wool will not produce dark lines on the photograph as deeper lines and other cuts and nicks will. Screens freshly cleaned with an abrasive should not be used for 24 hours, except when they will be in contact with film for very short time intervals. This caution is necessary because the fogging action is increased by the cleaning process.

In radiography with gamma rays, films loaded in metal cassettes not equipped with screens may record the effects of secondary electrons generated in the lead covered back of the cassette. These electrons produce a mottled effect on the film, due to the structure of the intervening felt pad. Films loaded in lead-backed cardboard exposure holders may also record the pattern of the paper separating the lead and the film. These and similar effects may be avoided with the use of lead foil screens on both sides of the film, as described previously. When, for any reason, screens are not available, the film should be encased in a lightproof paper or cardboard holder, without any metal backing.

One important caution must always be observed in the use of lead foil screens. This is a careful check to see that good contact is maintained between the film and screen. Otherwise, fuzzy images will result.

10–5.2 *Fluorescent Screens.* Fluorescent screens are made by mixing finely powdered chemicals, which have the ability to absorb X-rays and gamma rays and emit light (fluoresce), with a suitable binder and coating a special cardboard or plastic sheet with a thin, smooth glaze of the mixture. Films are clamped firmly between a pair of these screens during exposure. The photographic effect is intensified because it is the sum of the effects of the source radiation and of the light emitted by the screens.

Industrial radiographers seldom use fluorescent screens, since they are not employed with high energy as a rule. The reason is that they tend to give excessive graininess to the image. They may be used on occasion in the radiography of light metals or when economy demands shorter exposure time, which their use allows.

Normally, fluorescent screens emit a blue light when energized by radiation. They are used with film which has a high sensitivity to blue light. They are usually mounted in pairs in cassettes so that the fluorescent surface of each screen is in direct contact with the emulsion surface of the film. Poor contact results in blurred images. Protective surfaces, such as thin sheets of cellulose, should never be placed on screens.

Care must be used in the mounting and storage of fluorescent screens. The former is such a critical process that it is usually done by commercial concerns. If screens are mounted on the job, great care must be taken to avoid unevenness resulting from adhesives, etc. Dust and dirt particles must not be allowed to collect between the film and screen surfaces and screens must be kept free from stains. The sensitive surfaces of screens should never be touched. No cleaning should be attempted without consulting manufacturers' directions.

10–6 Film Processing

10–6.1 *Introduction.* Radiographic procedure is only partially completed once the exposure has been made. The chemical processing of the film used for the exposure is an important and exacting task. Improper processing may make it impossible to read film and render useless the most careful radiographic exposure work.

The exposure of film to ionizing radiations creates a chemical change which can be made visible through processing. In simple terms, the processing is designed to change chemically the silver bromide on the film, so that the "radiation shadow" cast by radiation passing through the specimen radiographed can be seen. There are five distinct steps in the processing of film: developing, stop bath, fixation, washing and drying. Each one is discussed in some detail here, as each will become part of the radiographer's routine work.

Certain general precautions apply to film processing as follows: (1) For consistent results, it is necessary to maintain within specified limits all chemical concentrations, solution temperatures, and processing time. (2) Scrupulous cleanliness is necessary to avoid streaks and spots on radiographs. (3) Tanks, trays, stirring paddles, etc., should be made from materials which resist attack by the processing chemicals. Acceptable materials are type 316 stainless steel, hard rubber, glass, and ceramics. Aluminum, zinc, copper, and tin must not be used since these metals contaminate the processing solutions and fog radiographs. (4) Suitable darkrooms should be equipped with subdued lights and filters which will not cause excessive "fog" on films.

10–6.2 *Developing.* Developing solutions have the ability to reduce the silver bromide crystals on the exposed part of films to metallic silver. At the moment the exposed film is put into the developer, the above process begins, and the longer the film is left in the developer, the more silver bromide is transformed and the denser the image becomes. Rate of development is also affected by temperature, with reaction increasing as temperature increases.

The radiographer will normally use commercially prepared developers in film processing. These come in powder or liquid form, which are dissolved in or diluted with water. Though more expensive, liquid developers are usually easier to prepare, a fact which may be of importance in some laboratories.

The time-temperature system should be used in the processing of all radiographic film. Following this system, the developer is always kept within a certain narrow range of temperature, and the time of development is adjusted so that the degree of development varies slightly, at the most. The contrast and density normally desired in industrial radiography films can usually be obtained with 5 to 8 minutes in a developing solution having a temperature of 68°F. or 20°C. Longer developing time is likely to produce chemical fog which will decrease contrast.

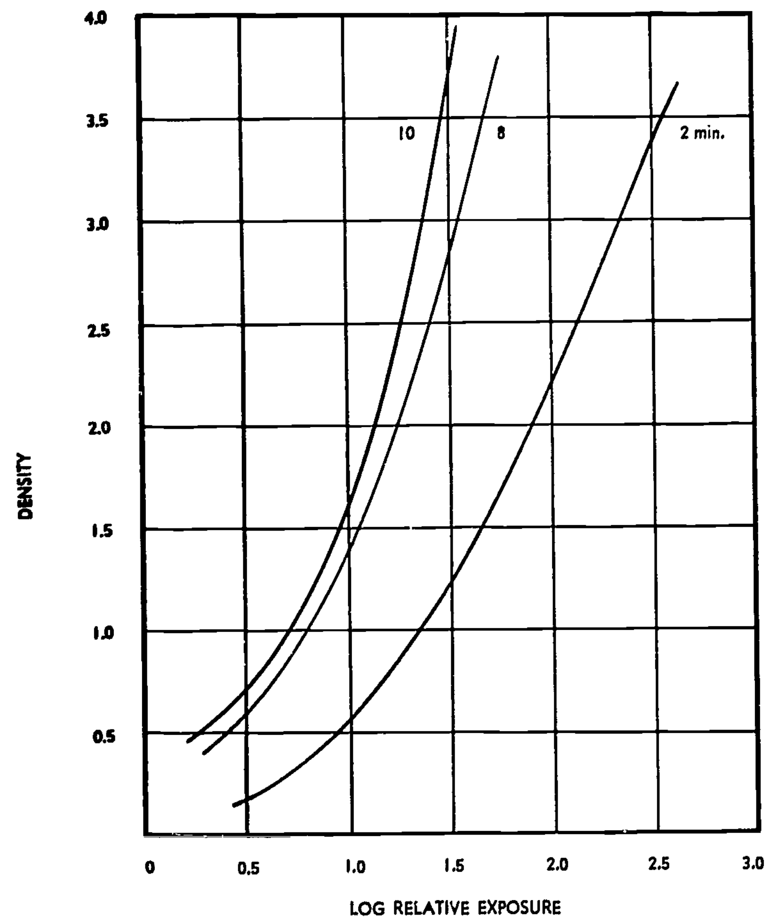


FIGURE 10.4.—Effect of Developing Time.

Temperatures for developing solutions should be checked immediately before the immersion of films. Temperatures below 68°F. will retard the action of the chemicals sufficiently to produce underdevelopment, while excessively high temperatures can fog the film or soften the emulsion on the film so that it will wrinkle or wash off.

It is never an acceptable practice to use guess work in developing film. For this reason, sight development, the examination of film to determine degree of development under safe light conditions, is not recommended. Sight development may result in fogging because of excessive exposure to the safe light. With reliable timing equipment and thermometers, one should have no difficulty in developing.

Two relatively simple procedures, in addition to time and temperature control, complete good development technique. First, it is necessary to agitate the film in order to secure uniformity of development. The reason for this procedure is that the reaction products of development have a higher specific gravity than the developer and thus flow downward, retarding the development of the areas over which they pass. The correct procedure is to lower the film hangers carefully into the developing solution, then tap the hanger bars (in tanks) to free air bubbles clinging to the emulsion. Sufficient agitation will result if the films are shaken vertically and horizontally and moved from side to side in the solution for a few seconds every minute of the development time.

The second procedure which must be observed is the replenishment of developer solutions. In the course of use a developer loses its chemical strength. This happens because of the exhaustion of the developing agent in the process of changing silver bromide to metallic silver and because of the restraining effect of the accumulated reaction products of the development. Developer solutions should be tested for activity at periodic intervals determined by use.

The easiest test for developer activity is to process film exposed in some standardized manner, and then to compare the density obtained with that obtained in a film developed in a fresh solution. For such a test, time and other exposure factors should remain identical.

The quantity of replenisher required can be determined by the solution manufacturer's directions.

10–6.3 *Stop Bath (Arresting Development).* Once the development process has been completed, it is necessary to stop the activity of the developer remaining in the film emulsion. This activity not only may result in uneven development, but the alkali of the solution retained by the gelatin will neutralize some of the acid in the fixer solution and shorten both its effectiveness and life. The activity of the developer is arrested by an acid stop bath solution. A stop bath may be made of 16 oz. of 28 percent acetic acid mixed with enough water to produce a gallon of solution. Stop baths can also be made by mixing 4½ oz. of glacial acetic acid per gallon of bath. When glacial acetic acid is used, great care should be taken because of the possibility of severe burns to the face and hands. The acid should be added slowly to the water (never the water to the acid) while stirring constantly.

The proper stopping procedure is to remove the film from the developer, allow it to drain a few seconds (but not into the developer tank), and then immerse it in the stop bath. Care should be taken to prevent the developer from draining off the film into the stop bath. (One way to prolong the life of the stop bath is to briefly rinse the film in running water prior to inserting it into the bath.) The film should be immersed in the bath for 30 to 60 seconds with moderate agitation. A stop bath temperature of 65° F. to 70° F. should be maintained.

If, for some reason, a stop bath cannot be used, the film should be rinsed in running water, free from silver or fixing chemicals, for at least 2 minutes. Moderate agitation is desirable if the flow of water in the rinse tank is not strong.

Five gallons of stop bath will treat approximately one hundred 14- by 17-inch films (or equivalent). The use of exhausted solutions will lower the quality of the radiograph.

10–6.4. *Fixation.* The developer does not change the unexposed silver bromide on the film, which means that the unexposed silver bromide remains in the emulsion and will darken upon exposure to light. To prevent this and the consequent ruining of the radiograph, a "fixer solution" is used which removes the unexposed silver bromide without changing the silver deposits which compose the desired image. The fixer solution also hardens the gelatin on the film so that it will stand drying with warm air. Such solutions are obtained from commercial suppliers.

The fixing time for film should be at least twice the time it takes to clear the undeveloped silver halide from the film (the clearing time). In a relatively fresh bath, fixing time is in the neighborhood of 8 minutes. Longer intervals are needed as the bath is used. When times in excess of 15 minutes are required, fixer solutions should be replenished to save time and maintain an adequate hardening action.

Films should be agitated vigorously when first placed in the fixing solution. Thereafter, agitation at two-minute intervals is advisable. Temperatures from 65°F. to 70°F. should be maintained in the bath, with care exercised to prevent warming in excess of 75°F.

Fixer solutions become exhausted through an accumulation of soluble silver salts and by dilution with rinse water or stop bath carried by the film. It is necessary to restore the solution at periodic intervals determined by the interval necessary to produce fixation. Otherwise, abnormal swelling of the emulsion will result and drying time will be unduly prolonged. The fixing solution may be maintained at a high state of activity through the simple process of adding suitable quantities of its component chemicals. A rule of thumb is to replenish the solution when fifty 14- by 17-inch films (or equivalent) have been fixed in 5 gallons of solution. At this time 32 ounces of the solution should be removed and replaced with 1 quart of undiluted fixing liquid, including hardener. Only two such replenishments are recommended for best results. (Refer to the solution manufacturer's instructions for replenishment recommendations.)

10–6.5 *Washing.* The next step in film processing is thorough washing in running water so that the fixer will be diffused from the film. Radiographic films should be washed in such a way that the entire emulsion area will receive frequent water changes. This can be accomplished by completely covering the film hangers and maintaining the hourly flow of water from 4 to 8 times the volume of the tank.

Washing tanks should be large enough to handle the flow of films from developing and fixing solution. Films fresh from fixing solutions should be placed near the outlet end of wash tanks and gradually moved to the inlet end as additional films are brought in for washing. In this manner, the final part of the washing process is done in fresh uncontaminated water.

Washing efficiency is closely related to water temperature with temperatures below 60°F. being very inefficient. Whenever possible temperatures between 65°F. and 70°F. should be maintained. As soon as washing is completed, usually from 20 to 30 minutes, the film should be removed from the tank, as gelatin has a tendency to soften with prolonged washing in water above 68°F.

10–6.6 *Drying.* After washing, films must be carefully dried. This is a relatively simple step, although caution must be used to remove the small drops of water clinging to the surface of the emulsion. The latter cause distortion of the gelatin and consequent changes in the density of the silver image. The best procedure is to immerse the washed film in a wetting agent (obtainable commercially) for 1 or 2 minutes and then allow them to drain for an additional 1 or 2 minutes. Wetting agents cause surplus water to drain off the film more evenly, preventing or greatly reducing water spots.

Radiographs dry best in warm, dry air that is constantly changing. Drying cabinets which circulate filtered and heated air give best results. If these are not available, the films, on their hangers, should be hung in a position where air freely circulates to dry uniformly both sides simultaneously.

10–7 Film Processing Facilities

All radiography operations include film processing facilities. For this reason the radiographer must know something about the room and equipment which should be included in such a facility. The purpose of this brief discussion is to describe the darkrooms and equipment which have proved satisfactory for industrial installations. Readers desiring more detailed information should refer to the specialized materials published on the subject, including the brochures of the various manufacturers of film processing equipment.

The location, design, and construction of a film processing facility will, of course, depend on the volume and character of the work which has to be done. Such facilities may range from a single room to a series of rooms, individually designed for each of the activities which have to be performed such as loading, developing, drying, etc. Smooth, efficient operation and easy accessibility should be kept in mind when planning darkrooms. Estimates of the number and type of film to be processed daily at peak operation should serve as a guide for the size of the room or rooms and equipment. It is just as important not to overbuild and waste space as it is to build a large enough facility to prevent crowding.

10–7.1 *The Darkroom.* The first concern in planning the construction of a film processing facility is the darkroom. Since excessive exposure of film to light will result in fog, great care must be exercised in the location and arrangement of lights. It is best to divide processing rooms and/or operations into three zones of light intensity: (1) the brightest can be normal white light for washing and drying film; (2) the intermediate safely lighted space for developing and fixing film; and (3) the dimmest safely lighted space for the loading bench. White light may be used for certain activities, such as mixing chemicals, cleaning tools, and unloading processing hangers.

The "safeness" of a lamp depends on using bulbs of the correct wattage, with the proper filter, located at the proper distance from the film. A thorough study should be made to assure safe light conditions are established and maintained. A simple method of checking illumination is to expose to the safelight a partially protected sample of the fastest film which is to be used in the processing room. After a time lapse equal to the maximum time needed for handling film, the test film should be run through the standard processing procedure and checked for greater density on the unprotected area. If the film shows no density increase, the light is safe.

The wall and floor covering of darkrooms is more or less critical to the film processing operation. Maximum reflectance of safelight is achieved with a cream or buff semi-gloss paint on walls where chemicals are not likely to be spattered. Walls near processing tanks should be covered with ceramic tile (free from radioactive materials), structural glass sheets, stainless steel, or certain plastics, to prevent chemical attack and staining. Floors must be resistant to chemical attack, as well as waterproof and slip-proof. Porcelain and natural clay tile or asphalt tile of darker colors are satisfactory. Linoleum and the plastic and rubber tiles stain or pit when processing chemicals are dropped on them.

Darkroom entrances must be designed to accommodate the number of people who must use the room and to utilize properly the amount of floor space available. A single door equipped with an inside lock is, of course, most economical of space. However, when more than one person is involved in film processing, it may not be practical. Two alternatives are possible: the light lock, made of double or revolving doors; and the labyrinth or maze, which effectively blocks outside light.

10–7.2 *Equipment.* Four major items of

equipment are standard in all film processing facilities: The loading bench, film storage cabinets and bins, processing tanks and film dryers. The so-called "dry" activities, such as the handling of unprocessed film, loading and unloading of cassettes and exposure holders, and the loading of processing hangers are all done at the loading bench. Loading benches should be located at some distance from the processing tanks to avoid water and chemicals. The loading bench area will also normally contain facilities for storing processing hangers and a light tight film storage bin.

The "wet" operations (developing, stopping, fixing, and washing) are accomplished in the processing tanks. It is mandatory that tanks be constructed of material resistant to radiographic chemical corrosion. (Most tanks are made of AISI Type 316 stainless steel with 2 or 3 percent molybdenum and have been fabricated in such a way as to avoid corrosion in weld areas.)

The insert tank capacity is critical because it determines the maximum volume of work which can be done. A five-gallon developer tank can handle approximately 40 radiography films an hour, at normal developing times. The stop bath tank should be the same size as the developer tank, but the fixer tank should be at least twice as large and the washing tank four times as large.

Plumbing for processing tanks is also a problem because of corrosion. Drainage lines may be of galvanized steel when waste solutions do not remain in the pipes. One additional caution must be observed. Under no circumstance should two metals subject to electrolytic action be used to make a connection. A common problem of this type occurs when galvanized steel fittings are attached to copper pipes.

10–7.3 *Film Dryers.* The recommended technique for film drying has been discussed elsewhere. However, the location and design of the dryer itself is one of the most important considerations in planning a film processing facility. Several types of dryers are available, including hot air, infrared, and desiccant types. Whichever model is chosen, it should be fast-acting; at the same time it should not overheat the films. It is advisable, as a precautionary measure, to use a filter on the air intake of dryers, although this may require a fan of large capacity. Removable drip pans under each film compartment are an aid to keeping the dryer clean.

10–7.4 *Automatic Film Processing Equipment.* In large scale operations it may be desirable to install automatic film processing equipment. These automatic machines save time and labor, and produce a very high degree of film uniformity.

Chapter 11

Radiography Techniques*

11–1 Introduction

The very large number of variables in the radiographic process requires that well organized techniques be prepared to interrelate conditions that can be controlled by the radiographer. Guess work and trial and error methods are too costly and time consuming for industrial operations. Background information related to these variables has been presented in the preceding chapters on an elementary but rather basic level. Such information is necessary for a general understanding of radiography.

The purpose of the following sections is to present information and techniques that have been proven useful and practical in industry. Use of these methods will enable a radiographer to attain reasonably good results with very little experience. A technician having a good knowledge and understanding of this material can devise his own shop practices when new specimens are to be tested. Improving practices and developing new techniques to secure high quality radiographs depend both on an understanding of general principles of radiography and experience in the shop and laboratory.

11–2 Exposure Calculations

More than 15 variables can be identified which must be controlled each time a radiograph is made. Making calculations with all of these variables is almost a mathematical impossibility and is certainly not practical. As a result of work by many laboratory and industrial experimenters, it has been proven acceptable for shop radiography that many of the conditions can be established and held constant. Others can be selected from tables and graphs. These can then be mathematically related to the remaining variables. The following are some of the variables that may be fixed, graphed, or tabulated.

11–2.1 *Chemicals and Film Processing.* Proper selection of equipment, safelights, and a darkroom arrangement as described in paragraph 10–7 will minimize film handling difficulties. Several manufacturers (see Appendix E) prepare and/or supply darkroom supplies and chemicals. To attain consistent results, the radiographer should select one group of chemicals, (1) developer with replenisher, (2) stopbath, and (3) fixer with replenisher, and then explicitly follow the manufacturer's directions for mixing, replenishing, film processing, and discarding depleted solutions. Any deviation can cause trouble. SCRUPULOUS CLEANLINESS is required in the darkroom to make good radiographs.

11–2.2 *Films.* Films are selected according to their speed and graininess. If the shortest exposure time is required, use high speed film. These films have coarse grain and will not give the best subject detail resolution. If the best resolution is required, the fine grain films should be selected and the much longer exposure time must be accepted. Contrast varies with film type and overall film density. Good practice indicates the minimum overall density should be not less than 1.5, and darker films are desirable if the viewing equipment has sufficient light intensity.

"Relative film speeds" are statements of radiation dosage required to expose a film to a specified density compared to some other film accepted as a standard. Table 11.1 contains relative film speeds and comparative contrasts of films used by industry.

TABLE 11.1.—Relative Film Factor.

Film Type	Density			
	1.5	2.0	2.5	3.0
High Speed (Coarse Grain)	0.8	1.3	2.1	2.4
Medium Speed (Medium Grain)	3.6	5.1	6.6	15.0
Low Speed (Fine Grain)	15.0	21.0	27.0	34.0

*Extracts from *Radiography in Modern Industry* published with permission of Radiography Markets Division, Eastman Kodak Company, Rochester, N.Y.

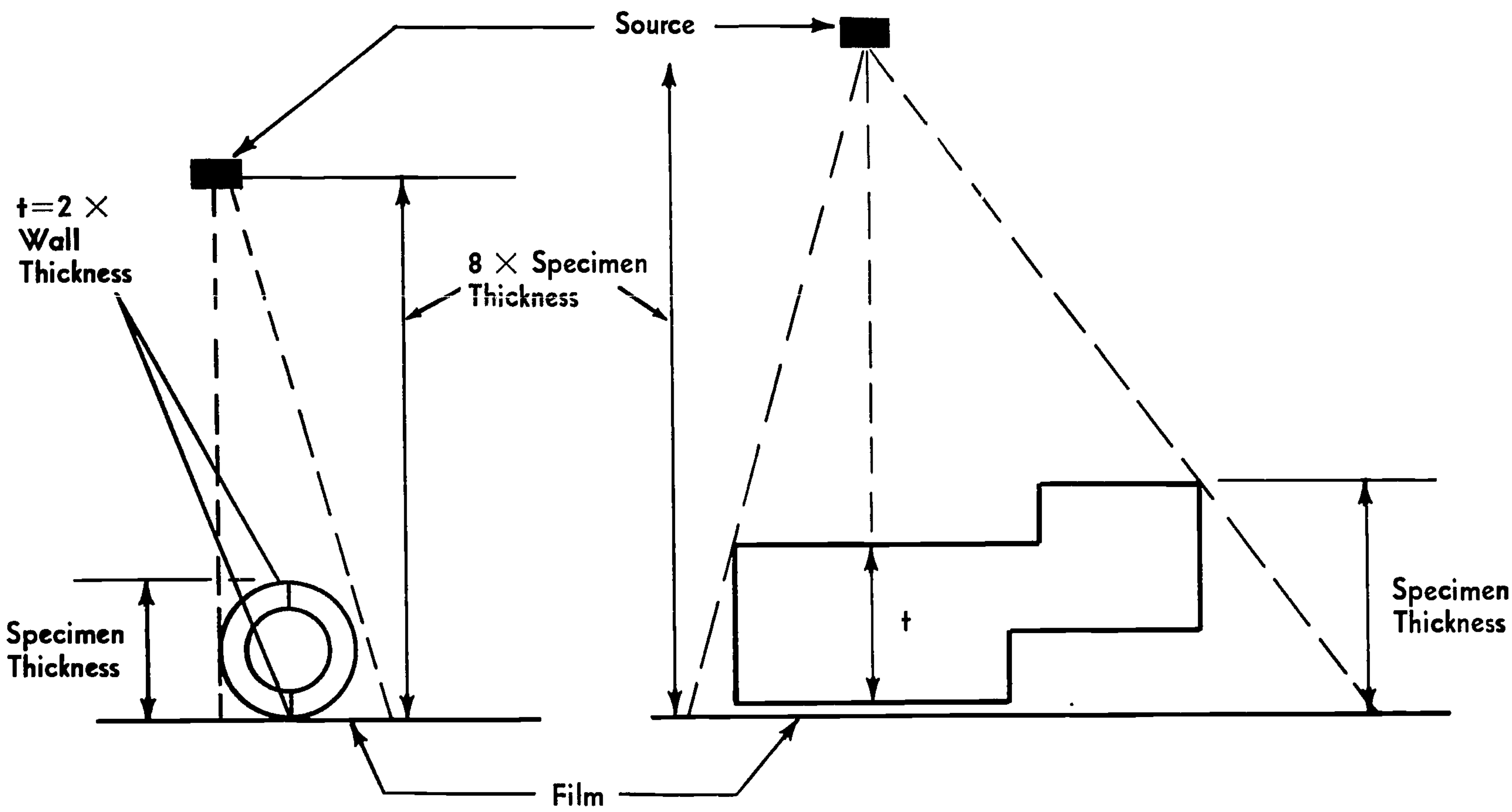
11–2.3 *Screens.* In paragraph 10–5, the action of screens was discussed. One screen should contact the film surface nearest the source (front screen), and one screen should contact the other film surface (back screen). Fluorescent screens are acceptable under some conditions. At higher energies they may cause undesirable graininess and lead-foil screens are generally used. Up to approximately 1 Mev, the front screen may be 0.005 inch lead-foil and the back screen may be 0.010 inch lead-foil.

11–2.4 *Geometry.* Geometrical variables are summarized in paragraph 9–2.5 and must be considered if acceptable detail resolution is to be obtained.

Arrangement of the position of the radiation source, specimen, and film will determine the geometric unsharpness. Through judgment and experience, the radiographer must develop a "feel" for the "geometry" of his techniques. Geometrical unsharpness is directly related to the (1) "source to specimen" distance, (2) specimen shape, and (3) source dimensions as shown in Figure 9.11. It has been stated that geometric unsharpness up to 0.010 is acceptable.

Every source has physical dimensions which will cast an undesirable penumbral shadow. When the X-ray machine or gamma ray source has been selected and delivered, the radiographer has no way to change source size. Gamma sources vary from 1/16 inch diameter to 1 centimeter diameter. X-ray target dimensions vary from 8 millimeters square down to a fraction of a millimeter. Target size and "permissible tube load" are interrelated. Both may be related to source costs; therefore, the radiographer must carefully select equipment before making purchases.

Specimen thickness and shapes will affect radiograph quality. If the specimen is long compared to the source to film distance, the extremities of the specimen will be underexposed because of the inverse square law and the longer absorption path at the extremities.



(1) For geometric unsharpness control, use source to film distance equal to or greater than 8 times the specimen thickness.

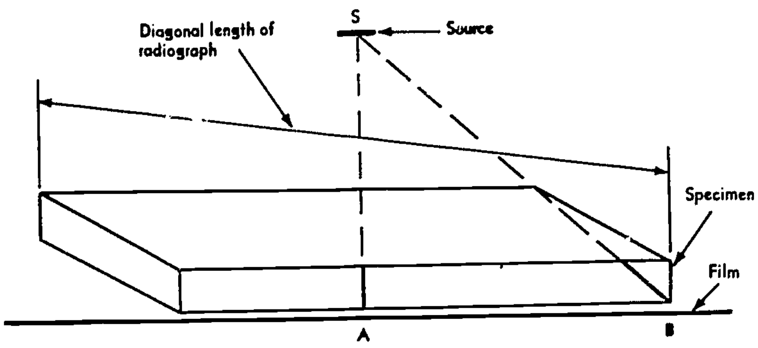
(2) For calculating exposure time, use the length of radiation path "t."

FIGURE 11.1.—Source to Film Distance.

Two widely used rules for guides in arranging geometry of techniques are:

(1) The source to specimen distance should be no less than 8 times the specimen thickness. If the specimen is a pipe or irregular shape, this thickness is defined as shown in Figure 11.1. Smaller ratios than 8 will cause undesirable distortion.

(2) The source to film distance should never be less than the diagonal length of the radiograph.



1. Path length B is longer than A, causing less radiation to reach the film at B.
2. The distance S to A is less than S to B, causing less radiation to reach the film at B.

FIGURE 11.2.—Source to Film Distance for Long Specimens.

11–2.5 *Specimen–Steel Equivalent Thickness.* X-ray and gamma ray energy production were discussed in paragraphs 9–1 and 9–2. Their interaction with matter was discussed in paragraphs 4–3, 4–5, and 4–6. In the energy range used for industrial gamma radiography, the gamma radiation interaction with matter is somewhat related to subject density. For this reason tables and graphs can be simplified by expressing metal thickness in terms of "steel equivalent thickness" (S.E.T.). As an example, the density of aluminum is 168 lbs. per cu. ft., while the density of steel is 492 lbs. per cu. ft. Therefore, the steel equivalent thickness of aluminum is:

$$\text{S.E.T. (Aluminum)} = \frac{\text{Density of Aluminum}}{\text{Density of Steel}} = \frac{168}{492}$$

$= 0.34$ inch of steel radiation absorption approximately equivalent to one inch of aluminum (for the energy range most often used for isotope radiography)

Table 11.2 gives the steel equivalent thickness of metals frequently used in industry. These values are acceptable for exposure calculations using radioisotopes.

TABLE 11.2.—Steel Equivalent Thickness of Metals (for gamma rays only).

Metal	Density lbs. per cu. ft.	Steel Equivalent Thickness (S.E.T.)
Magnesium	108	4.54
Beryllium	115	4.27
Aluminum	168	2.93
Iron (Steel)	492	1
Copper	557	0.884

11–2.6 *Radiation Energy Versus Specimen Thickness.* The atomic number and thickness of the specimen determine the radiation energy (kev or Mev) that must be used to penetrate the subject and expose the film. Table 11.3 for X-rays and Table 11.4 for gamma rays give information that has been proven useful. Within these ranges, 2 percent sensitivity (see paragraph 12–3) can be obtained. Outside these ranges the sensitivity may not be as good as 2 percent but the radiograph may be satisfactory, depending upon the specimen and acceptable discontinuities.

TABLE 11.3.—X-ray Energies and Applications (a guide for inexperienced radiographers only).

Maximum Tube Voltage, Kvp	Steel Equivalent Thickness, Inches
150	Up to 1½
250	Up to 3
400	Up to 4
1,000	Up to 6
2,000	Up to 8
24,000	Up to 20

TABLE 11.4.—Radioisotopes and Applications.

Isotope	Mev	Steel Equivalent Thickness, Inches	
		Minimum	Maximum
Co-60	1.17 and 1.33	1½	7
Cs-137	0.66	⅝	3½
Ir-192	.4 Avg.	⅜	3
Tm-170		.....	⅜
Gd-153		.....	⅜
Sm-145		.....	⅜

EXPOSURE CALCULATION DATA
for Co–60, Cs–137, and Ir–192

using equation: $T = \frac{FAD^2}{S}$ where:

T = exposure time (minutes)
F = film factor (from table)
A = absorber factor (from curve)
D = source to film distance (inches)
S = source activity (millicuries)

Additional requirements

1) Lead intensifying screens to be used 0.005" front 0.010" back
2) Development— 8 minutes at 68°F.
3) Emission values for determining source activity:
Co–60—14.4 mr/mc hr at 1 ft.
Cs–137—4.2 mr/mc hr at 1 ft.
Ir–192—5.9 mr/mc hr at 1 ft.

Table of Film Factor—"F"

Film Type	Density 1.5	2.0	2.5	3.0
High Speed (Coarse Grain)	0.8	1.3	2.1	2.4
Medium Speed (Medium Grain)	3.6	5.1	6.6	15.0
Slow Speed (Fine Grain)	15.0	21.0	27.0	34.0

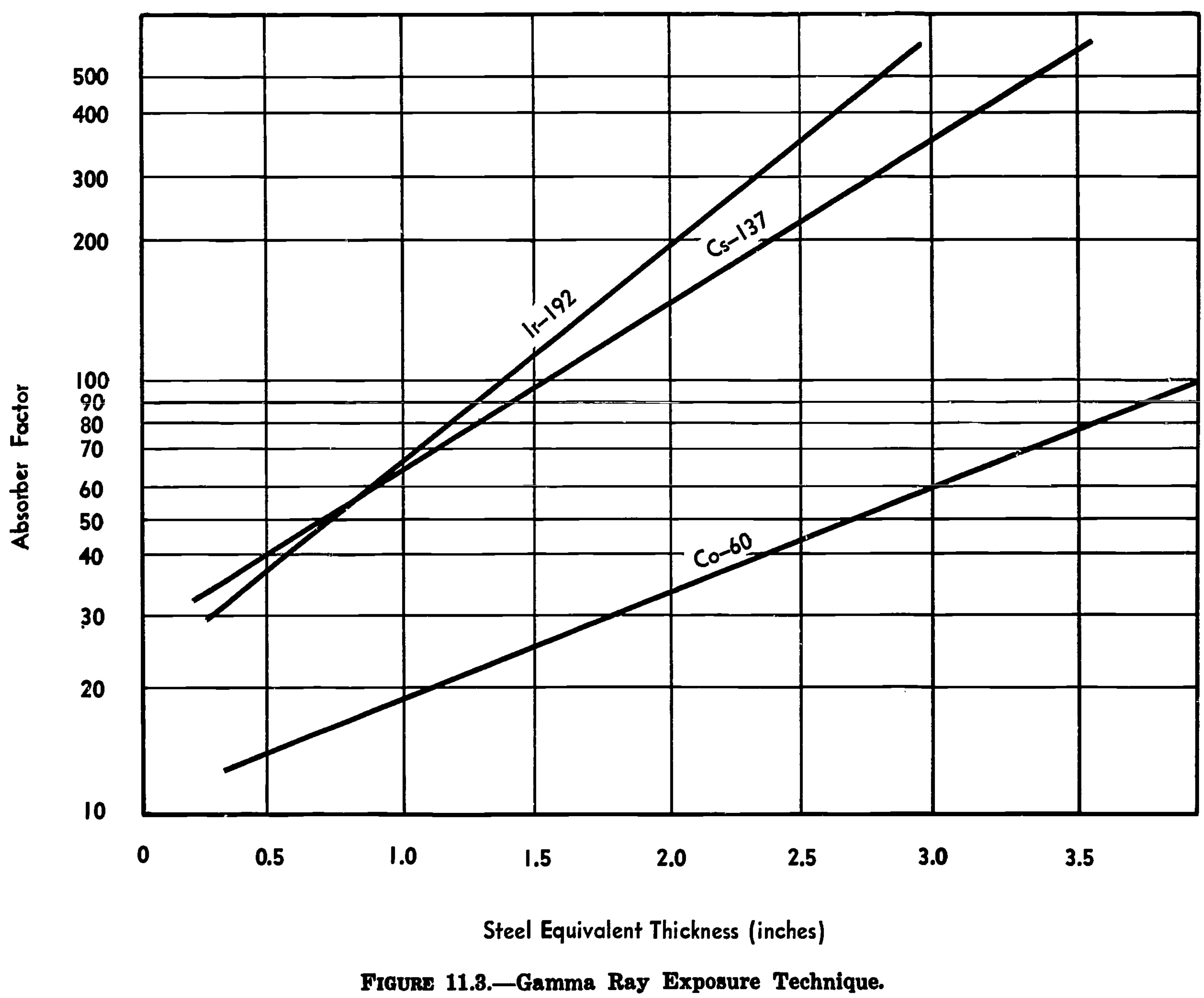


FIGURE 11.3.—Gamma Ray Exposure Technique.

11–2.7 *Source Emissivity.* Darkening of the film is determined by the exposure time multiplied by the amount of radiation reaching the film. It is obvious that the amount of radiation reaching the film must be related to the radiation emitted from the source. For radiography isotopes, Table 9.1 gives the emissivity expressed in the units roentgens per curie (or milliroentgens per millicurie) hour at the unit distance of one foot. Every source has its own emissivity which is a constant. The total energy emitted by any given source is determined by multiplying its emissivity times the number of curies in the source. A typical radiography source would contain 30 curies of Ir–92 having emissivity of 177 r/hr @ 1 ft. This must, in some way, be included in exposure calculations. Figure 11.3 and paragraph 11–2.8 show that emissivity is accounted for in the equation by expressing the source activity in millicuries.

For many reasons the emission rates from X-ray machines cannot be as easily stated as for radioisotopes. Energy emission rates from industrial X-ray machines be quite high, requiring very careful techniques to prevent personnel overexposure. For example, an X-ray machine operating at 300 Kev and 10 ma could emit 140 roentgens per minute at 0.5 meter. (These are the units used most often in connection with X-rays.) In units used with isotopes, this would be an emissivity of 22,890 r/hr @ 1 ft., equivalent to the energy emitted from 3,880 curies of Ir–192.

In exposure calculations for X-ray machines, a simplification is to express the energy emitted in terms of milliampere-minutes (ma-min.). This means the tube current in milliamperes is multiplied by the minutes of exposure time. The number of roentgens emitted is not actually determined but is accounted for by including milliampere-minutes in the calculations shown in paragraph 11–2.9 and Figure 11.5.

11–2.8 *Gamma Ray Exposure Time.* The exposure time must be determined for each radiograph. For gamma ray techniques this can be done by using Figure 11.3 and the following steps:

(1) Measure the specimen absorption path thickness "t" and determine the steel equivalent thickness. From Table 11.4, select an isotope appropriate for that thickness. Determine the source activity, in millicuries, from that isotope's calibration curve.

(2) Measure the longest dimension of the specimen to be radiographed. Determine the source to film distance according to paragraph 11–2.4.

(3) Select the film type to the resolution required. From the table on Figure 11.3, select the film factor "F" in the desired density column.

(4) From Figure 11.3, determine the absorber factor "A" by:

  (a) entering the bottom of the sheet at the appropriate S.E.T. value
  (b) vertically follow that S.E.T. line to intersect the selected isotope line
  (c) from that intersection, follow a horizontal line across to the left margin
  (d) where that horizontal line reaches the margin, read the value of the absorber factor.

(5) Calculate the exposure time, "T," in minutes, by substituting numerical values into the equation shown on Figure 11.3, $T = FAD^2 \div S$.

Example: The specimen shown in Figure 11.4 is to be radiographed. Selections of technique details will follow those outlined in paragraph 11–2.8.

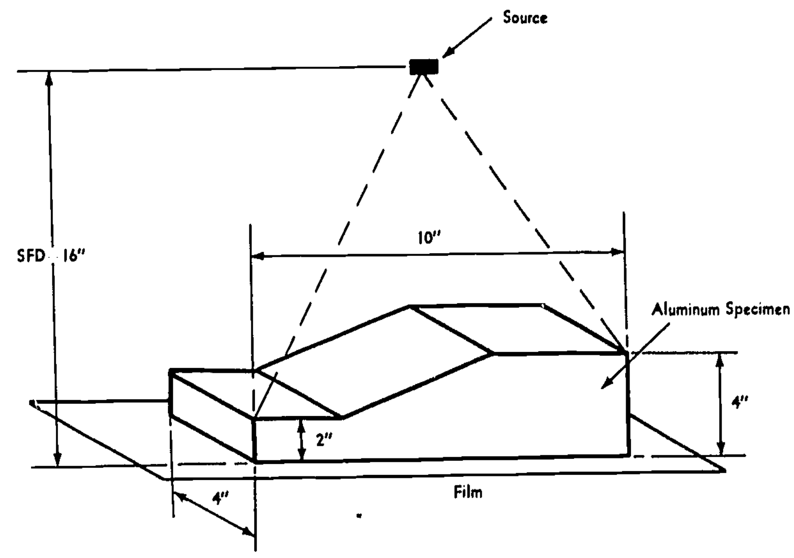


FIGURE 11.4.—*Example*—Specimen For Exposure Calculations.

Step 1: Thickness is 4″. The specimen is aluminum. Its steel equivalent thickness (S.E.T.) is $4'' \div 0.34 = 1.36''$. From Table 11.4, select Ir–192. For this example, assume the source calibration curve gave 30.8 curies of Ir–192.

Step 2: (a) The longest dimension to be radiographed is $\sqrt{10^2 + 4^2} = 10.6''$; therefore, the minimum source to film distance must be greater than 10.6″ (b) the specimen thickness is 4″; therefore, the minimum source to film distance must be $8 \times 4'' = 32''$ or greater (c) use a 32–inch minimum source to film distance.

Step 3: Medium speed film is acceptable. From the film table on Figure 11.3, select the film factor "F," 3.6, from the 1.5 density column.

Step 4: From Figure 11.3, determine the absorber factor "A" by (a) entering the bottom of the curve at the S.E.T. value for the specimen, (b) following the 1.36″ line upward to intersect the Ir–192 curve, (c) from that point following a horizontal line to the left margin and (d) reading the absorber factor "A," 95.

Step 5: Calculate "T" in minutes:

$$T = \frac{FAD^2}{S} = \frac{3.6 \times 95 \times 32^2}{30{,}800 \text{ mc}} = 11.3 \text{ min.}$$

11–2.9 *X-ray Exposure Time.* Calculation of X-ray exposure time is not as simple as for gamma rays. The reasons for this are the complex equipment, controls, and energy spectrum. Measurements can easily be made of (1) source to film distance, (2) tube current, (3) milliamperage, and (4) exposure time; however, tube voltage is difficult to measure accurately. Designs of X-ray machines and their tubes vary between manufacturers so that the amount and quality of energy emitted may be quite different, even though they are operating at the same voltage and current.

It is possible to prepare exposure technique curve sheets that will reproduce conditions for films, source to film distance, milliamperage, and exposure time. Accounting for variance in kilovoltage settings often requires trial exposure to attain the desired radiographic density. Exposure charts provided by the film and X-ray machine manufacturers may be used as guides. The radiographer should make trial exposures to determine correction factors for the charts. A log book could be kept so the radiographer will have information for developing techniques for new specimens.

A typical X-ray exposure technique curve sheet is shown in Figure 11.5. Charts of this type are prepared for a specific set of conditions as listed:

(1) The X-ray machine is identified because the amount of energy and the energy spectrum will not be the same for all machines
(2) The material and thickness of added filters
(3) Film type and film density
(4) Source (target) to film distance
(5) Specimen material

If any of the conditions are changed the radiographer must obtain or prepare a new chart or make some necessary corrections.

The curve sheet will permit accounting for the (1) specimen absorption path length, t, (2) kv applied to tube, and (3) exposure expressed in milliampere minutes, ma-min.

An X-ray tube has an energy emission rate determined by the tube current, ma. Exposure is the product of beam intensity and time. Up to the maximum tube current specified by the manufacturer, the radiographer may select any milliampere, ma, value. This selected ma divided into the milliampere minutes obtained from the curve sheet will determine the exposure time in minutes.

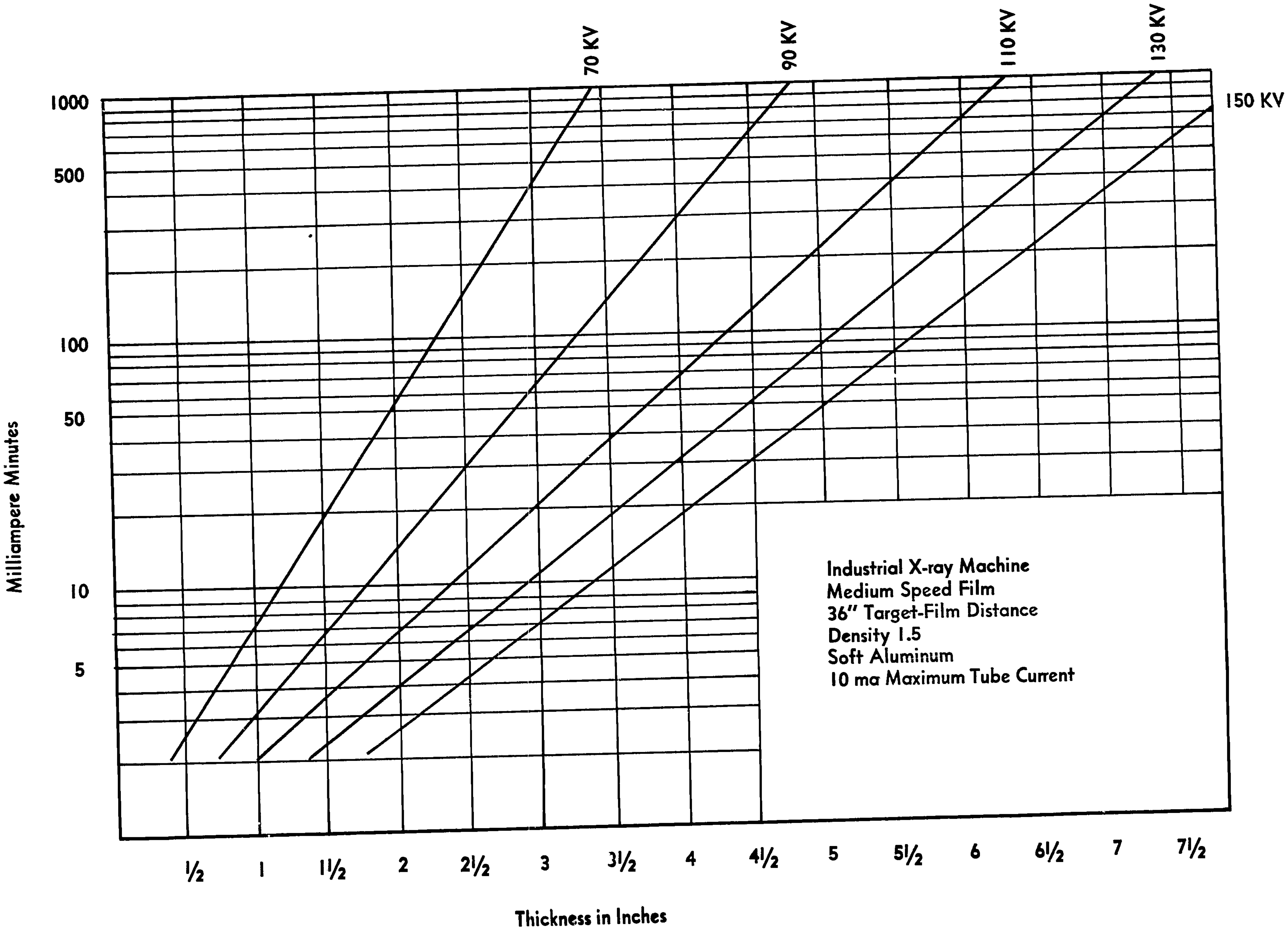


FIGURE 11.5.—X-ray Exposure Curves.

Example: Suppose that the ma-min value for an exposure was determined to be 24. The radiographer could select 8 ma with a corresponding 3-minute exposure time. An identical result could have been obtained by selecting 6 ma with a corresponding 4-minute exposure time.

Example: The specimen in Figure 11.4 is to be radiographed. Select the conditions and use Figure 11.5 to determine the exposure time. This specimen is 2″ thick, aluminum.

Step 1: Medium speed film at density 1.5 will give acceptable resolution.

Step 2: From Table 11.3 it is determined that 150 kv is suitable.

Step 3: (a) The longest dimension to be radiographed is $\sqrt{10^2 + 4^2} = 10.6''$; therefore, the minimum source to film distance must be greater than 10.6″ (b) the specimen thickness is 2″; therefore, the minimum source to film distance must be $8 \times 2'' = 16''$ or greater (c) use a 16″ minimum source to film distance.

Step 4: From the 2″ thickness line on the bottom of Figure 11.5, follow a line vertically upward to intersect the 150 kv curve. From that intersection, follow a horizontal line to the left margin at 2.7 ma-min. Select any ma value which is not greater than 10 ma, e.g., 3 ma. Exposure time $= 2.7 \div 3 =$ 0.9 minutes (not accounting for SFD) Correcting for SFD: $0.9 \left(\frac{1.6}{36}\right)^2 =$ 0.2 min. exposure time.

11–2.10 *Control of Scatter.* Scattered radiation cannot be completely eliminated, but may be reduced to minimize loss of image contrast. Some of the ways to reduce the amount of scattered radiation which reaches the film include (1) lead-foil screens, (2) protection from back scatter, (3) filters, and (4) masks and diaphragms. Lead-foil screens placed in direct contact with both sides of the film decrease the effect of scattered radiation on the film. The foil absorbs the longer wavelength scattered radiation more than it does the primary radiation. Also, it increases the photographic action of the film due to the emission of electrons and secondary X-radiation. Because of this "intensifying" action, lead-foil screens may result in less exposure time. By removing scattered radiation, however, they improve the quality of the image except at a very low voltage. At a sufficiently low voltage the front foil screen may absorb enough primary radiation to lower image quality. Some film holders or cassettes provide for a pair of thin lead-foil screens to be in direct contact with the front and back side of the film.

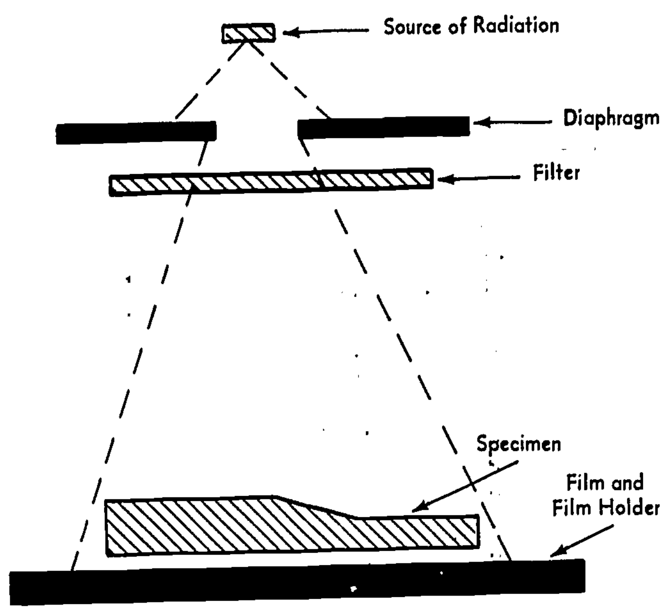


FIGURE 11.6.—Filter Near Source of Radiation.

Back-scattered radiation can result in very low quality images. Many exposure techniques provide a rather thick sheet of lead on the back side of the film holder to prevent back scatter from reaching the film. This is usually sufficient for X-ray radiography using voltages below about 100 kilovoltage. Above 100 k.v., thicker lead is needed, up to about ¼ inch at 1 Mev. Usually the table or floor on which specimens and film are placed is covered with the lead. When film holders are fitted with the sheet of lead to prevent back scatter, some precautions must be taken when using gamma rays or X-rays above 200 k.v. Secondary radiation from the lead sheet may affect the image quality unless the film is enclosed between lead-foil or intensifying screens.

Filters are sometimes used with X-ray radiography. Lead, steel, copper, or brass are used as filters. A filter mounted near the X-ray tube between the source and the specimen serves a very useful purpose. Such a filter absorbs more of the "soft" or low-energy X-rays than the "hard" or high-energy X-rays. This helps prevent overexposure of thin areas of the specimen. Also, such a filter reduces the undercut near the edges of the specimen. Such a filter makes a longer exposure time or an increased kilovoltage necessary, but this is usually not a problem.

If a specimen has very thin sections adjacent to thick sections, or if the primary beam may reach film near the specimen, undercut may occur. A filter placed near the X-ray tube will help prevent undercut and overexposure of the thin sections. By absorbing more of the "soft" radiation, lower subject contrast results. This permits a wider range of specimen thicknesses to be shown. No tables of filter thicknesses are available. The amount of filter action needed for a good image depends upon the material and thickness of the specimen, upon the range of specimen thicknesses, and upon the amount of undercut likely to occur. Experience has shown that in the radiography of steel, a lead filter about 3 percent or a copper filter about 20 percent of the maximum steel thickness gives good results.

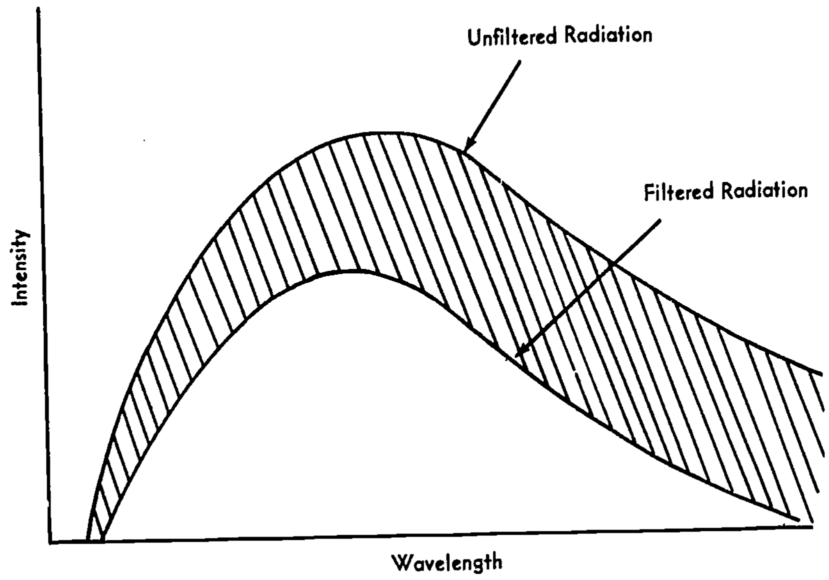


FIGURE 11.7.—Effect of Filter on Intensity of X-ray Radiation.

Up to 250 k.v., filters should be placed near the X-ray tube. However, in million-volt radiography, filtration at the tube does not seem to improve the quality of images. Lead filters between the specimen and the film have been found useful, but care must be taken to avoid defects in the lead filters lest these show on the film and be mistaken for specimen defects.

When a specimen has high absorption of X-rays, scattered radiation from external sources may be high compared to the primary radiation reaching the film through the specimen. This results in a poor quality image. Such scatter may be lessened by the use of a mask cut out and placed around the specimen. For example, a sheet of lead may be used as a mask and an opening cut in the sheet the same shape as the specimen, but slightly smaller. The lead reduces the radiation received by objects around or near the film and hence the scattered radiation received by the film. A lead diaphragm may be used near the source to limit the cross section of the primary beam to the shape or size of the specimen in order to reduce scatter. Also, if only a part of the specimen is to be radiographed, a lead diaphragm may be used to mask off unwanted parts of the specimen.

In some cases, barium clay may be packed around a specimen to serve the same purpose as a mask. Also, metallic shot of .01 inch diameter or less may be used with irregularly shaped objects. These fill holes or cavities and prevent overexposure of thin areas where there are also thick areas to expose.

11–3 Exposure Arrangements

Proper location of the source and film, with respect to the specimen, may determine the quality of the radiograph. With experience, the radiographer will become proficient at selecting the best arrangement.

General questions for the radiographer to keep in mind are:

(1) Which arrangement will give the best radiographic contrast of the specimen area that is likely to contain manufacturing discontinuities?

(2) **Which arrangement will give the best radiographic contrast of the specimen area that is likely to fail under imposed operating stresses?**

(3) **Which** arrangement will allow the **shortest** exposure time?

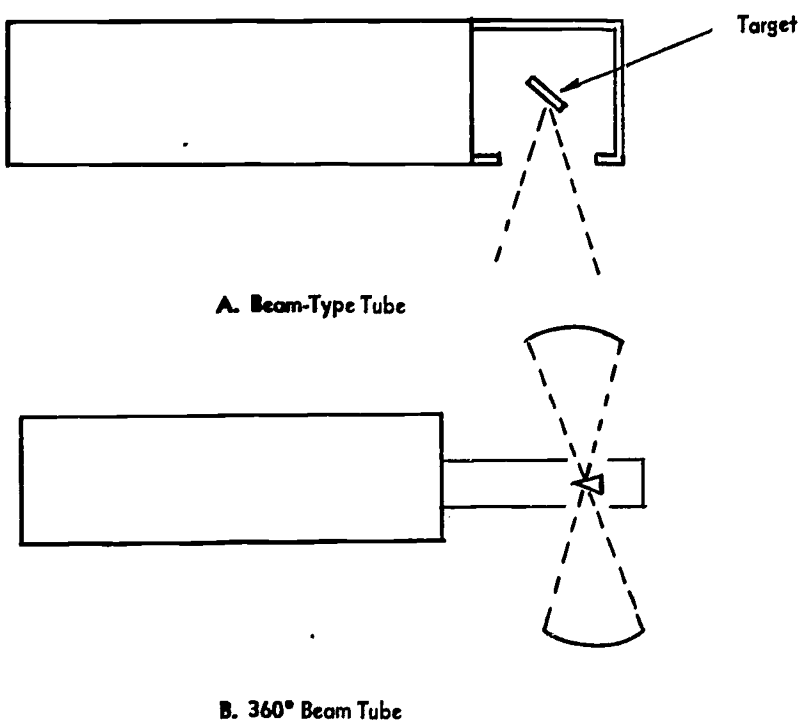


FIGURE 11.8.—X-ray Tube Beams.

(4) Will the specimen contrast require (a) single film, (b) double film, or (c) multiple exposure technique?

(5) Can beam or panoramic radiations be more appropriate?

X-ray and gamma ray equipment can be designed to emit the usable radiation in a beam, see Figures 11.8A and 11.9A and B. Shielding in the equipment is arranged to control the radiation intensity in all directions except the beam. X-ray tubes are available which produce a narrow, 360° radiation beam. This is particularly useful for simultaneously radiographing several small pieces (see Figure 11.14) or an entire circumferential weld (see Figure 11.12). The gamma ray device in Figure 11.9 emits its radiation with a 360° spherical beam. It is useful for the same application as the 360° X-ray tube. Also, the spherical beam has been used with a single exposure to radiograph all the welds on a spherical pressure vessel (see Figure 11.13).

Several sketches will demonstrate applications of exposure arrangement. A flat weld area, Figure 11.10A or B, is one of the simplest subjects to radiograph. Its critical area is well defined in length, width, and thickness. Subject contrast is not excessive.

A welded Tee joint, shown in Figure 11.10B, presents a different problem. The weld root is the area most likely to contain weld defects. No convenient location for the film can be found that will give good weld root image resolution. Either of the arrangements can be used. It should be noted that the object film distance is quite large in view number 2, and in this circumstance good resolution can be attained only by using a very long source to film distance.

Radiography of pipe welds can require additional arrangements. If the pipe diameter is small, i.e., 1½ inches or less, the entire weld may be exposed on a single film. The source at A would project the images of both pipe walls onto the same film area. It would not be possible to determine which pipe wall contained a defect if one were present. A better arrangement is to place the source offset from the plane of the weld (see Figure 11.11 A.) The weld image will be cast onto the film as an ellipse, which will reveal the location of weld discontinuities.

On radiographing welds of larger pipe, the radiographer will find difficulty determining the length of the radiation path through the specimen for calculating exposure time. In Figure 11.11 B, it is apparent that the thickness along path P is much less than along the path near a tangent to the pipe. The radiograph along path P will be much darker than the tangential area. It is practically impossible to make an acceptable radiograph of larger pipe on a single film. A better procedure is to divide the weld circumference into 3 or 4 segments and radiograph each with a separate exposure. If the pipe has a diameter 12 inches or greater, and its interior is accessible, a widely used arrangement is that shown in Figure 11.12. This technique is most useful in pressure vessel radiography.

All welds on spherical and hemispherical pressure vessels can be radiographed with a single exposure. Film holders cover all welds. The radioisotope source is placed at the geometric center, and the 360° beam front exposes all areas at the same time. This saves much

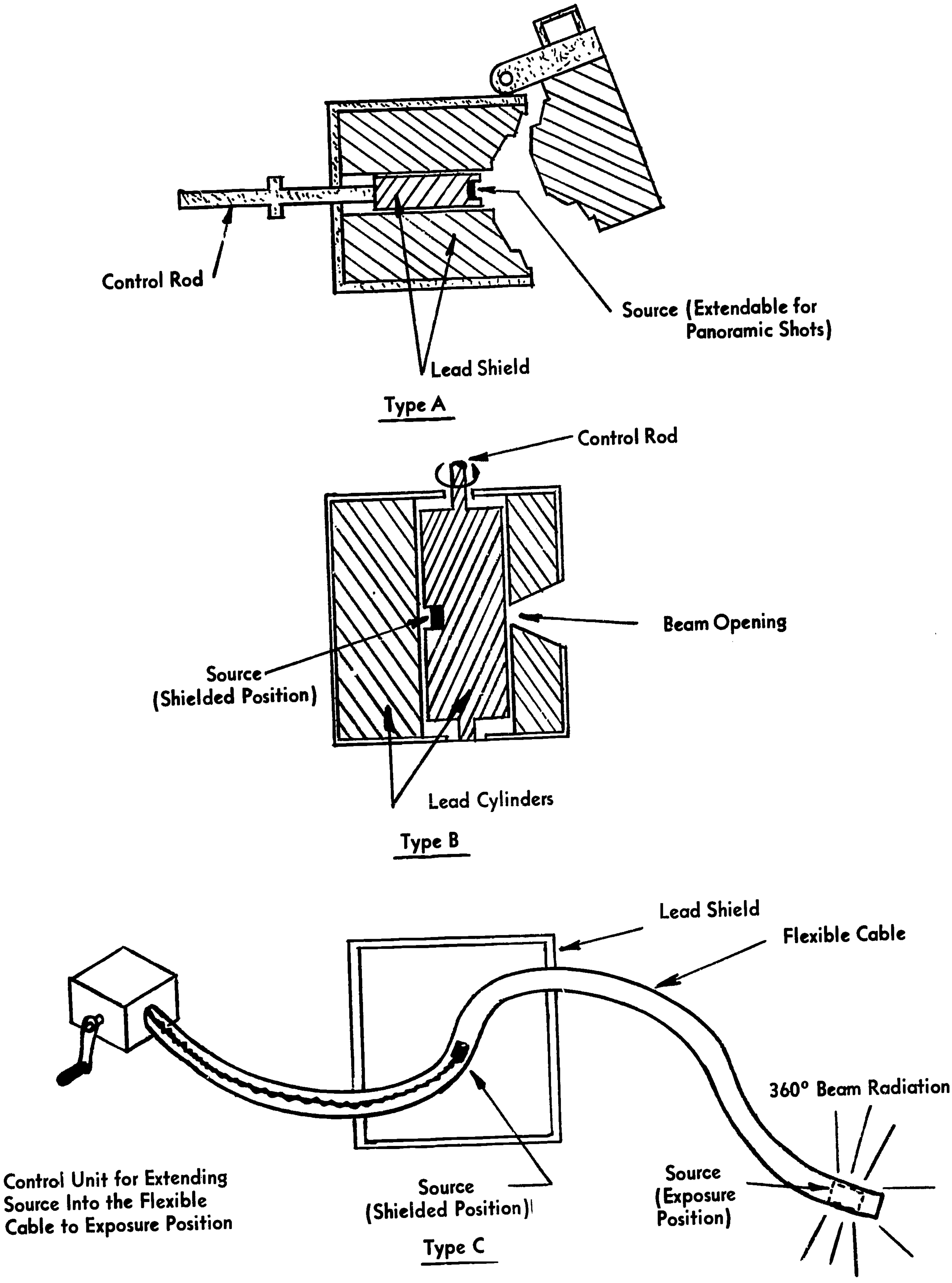


FIGURE 11.9.—Gamma Ray Exposure Devices.

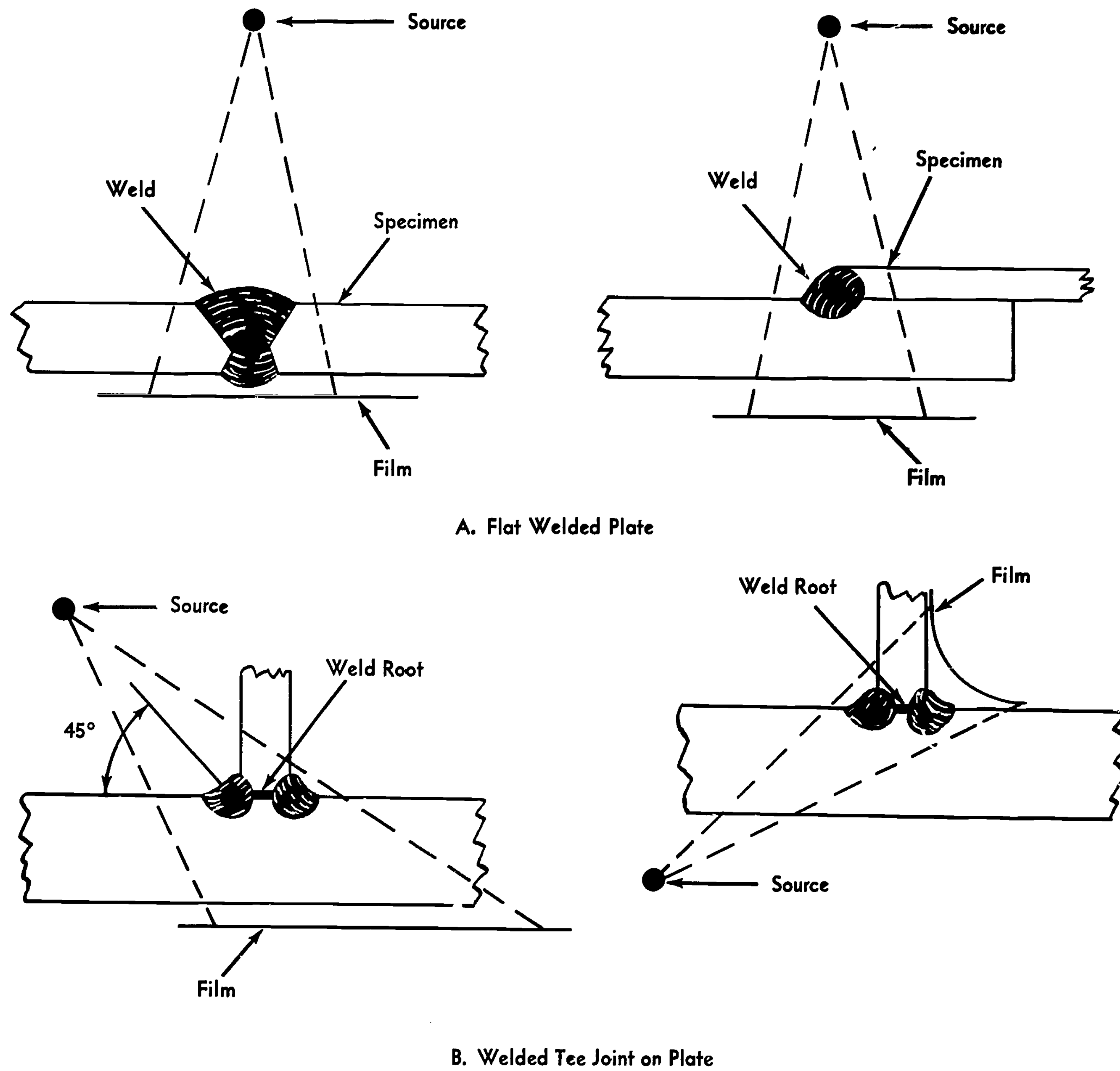


FIGURE 11.10.—Welded Flat Plates.

"set-up" time required for radiographing the many small areas covered by a beam forming source. (Figure 11.13)

When large numbers of small parts are to be radiographed, a panoramic exposure arrangement may be used (see Figure 11.14).

Some specimens have very large subject contrast. The thickness range may not be possible to radiograph on a single film with a single exposure (see Figure 11.15). In such cases, several different techniques may be acceptable:

(1) Using the same type of film, make 2 radiographs, one for section A and one for section B.

(2) Place two pieces of the same type of film in the holder and make a single exposure. During interpretation, read a single film for section A, and superimpose the films on the viewer for viewing section B.

(3) Place one high speed film and one slow speed film in the film holder for a single exposure. Read section A on the slow film and read section B on the fast film.

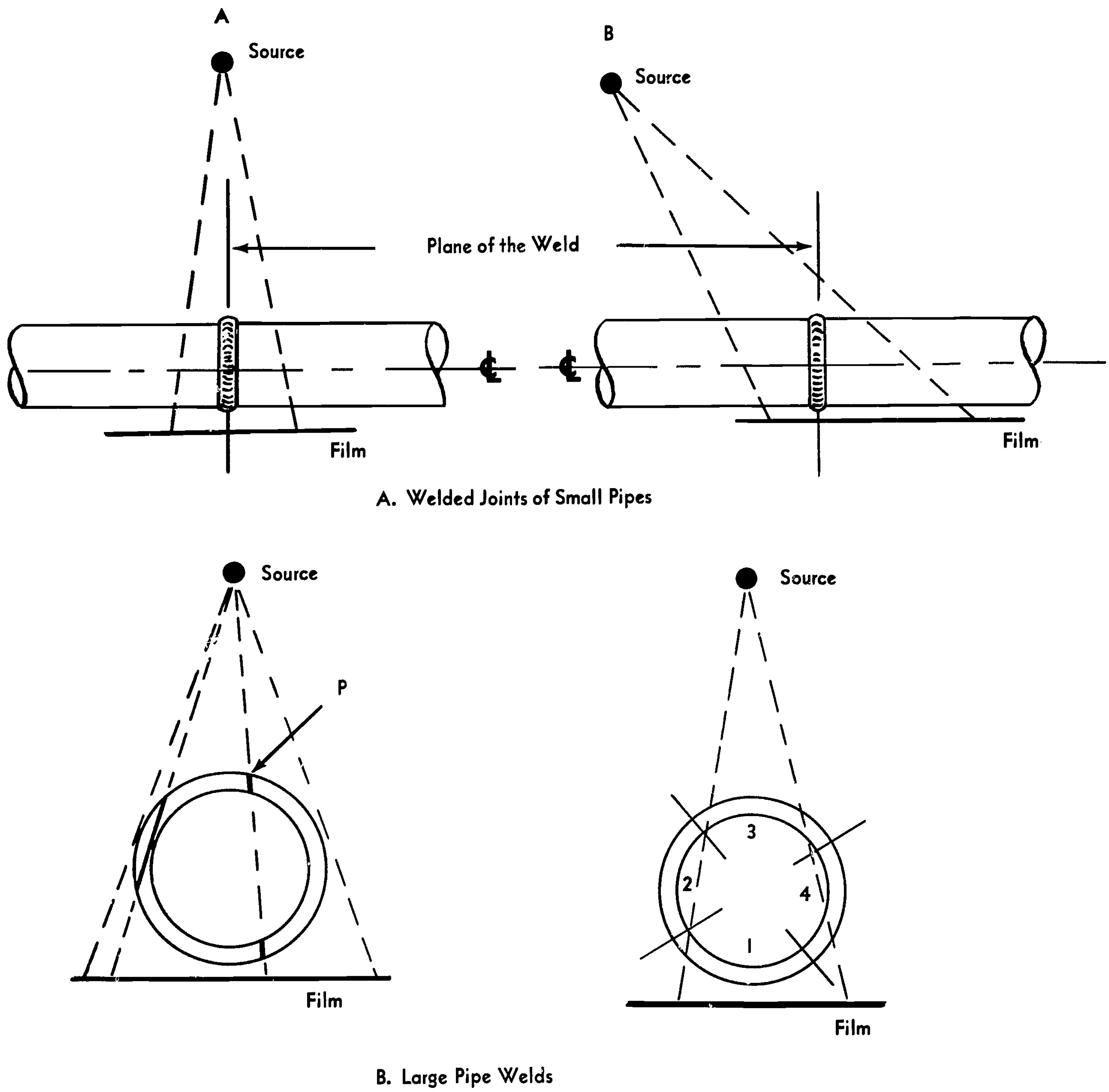


FIGURE 11.11.—Welded Joints of Pipe.

11–4 Unsatisfactory Radiographs: Causes and Corrections

It is not unusual for a radiograph to be unsatisfactory despite many laborious procedures. The radiographer should try to locate the source of error and prevent a recurrence. This section is designed to be of use in locating the more common faults which lead to poor quality radiographs. The characteristics of the unsatisfactory film provide a convenient reference.

11–4.1 *High Density*. An excessively high film density can be caused by: (1) overexposure, (2) overdevelopment or (3) fog (to be discussed later). Overexposure is normally caused by an incorrect exposure factor and can be corrected by decreasing exposure time by one-third or more. Meters and timers should be checked for accuracy if this trouble persists. Sometimes an overexposed film can be read well enough to be used, if illumination of higher intensity is provided.

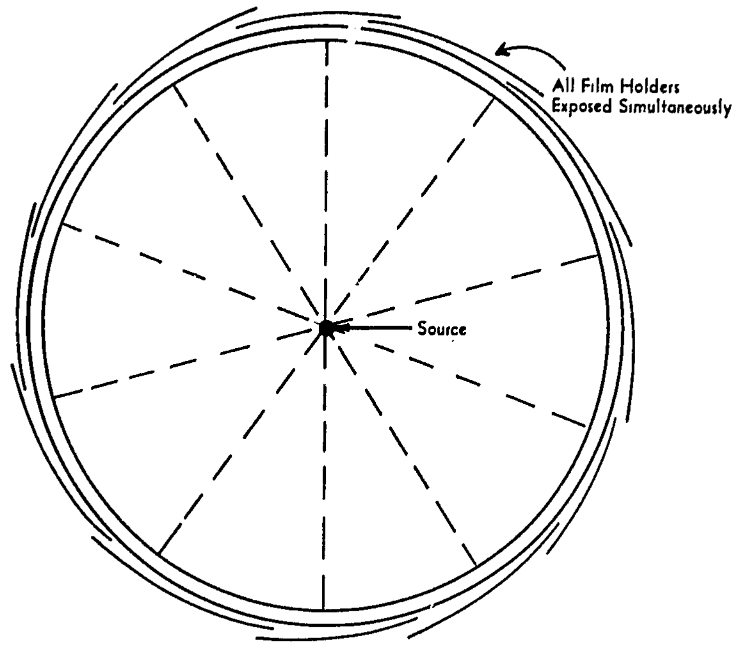


Figure 11.12.—Radiographing Welds of Larger Diameter Pipes and Pressures Vessels.

Overdevelopment is a function of one of two things: Too long a development time or too warm a developer solution. Simple checks will determine whether one or both conditions should be corrected.

11–4.2 *Low Density.* The presence of one or more of these conditions generally accounts for inadequate film density. First, exposure factors may be incorrect. When this condition is suspected, an increase of 40 percent or more in exposure time is recommended. Second, the film may be underdeveloped, for a number of causes. Either the development time is too short, the developed solution is too cold, or the developer solution is too weak. Such conditions can be checked and corrected if found abnormal. Finally, it happens on occasion that an intervening material, such as paper, is left between the screen and the film. This possibility should be checked out if other errors do not reveal the trouble.

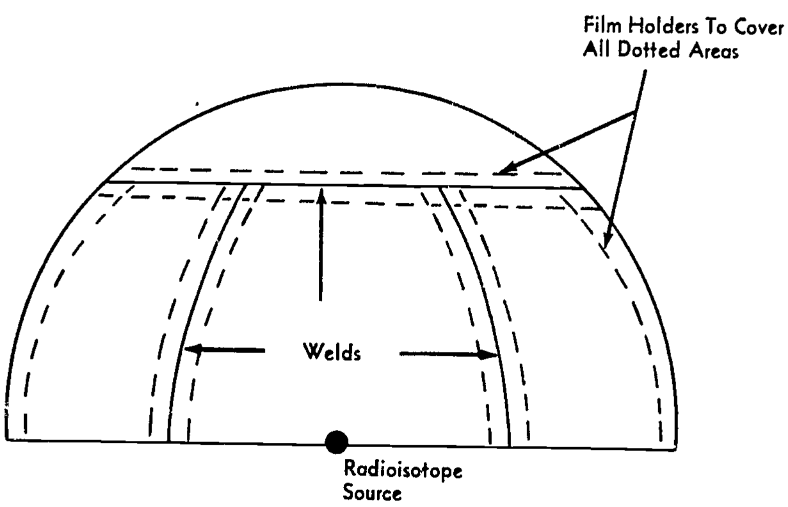


Figure 11.13.—Hemispherical Orange Peel Head.

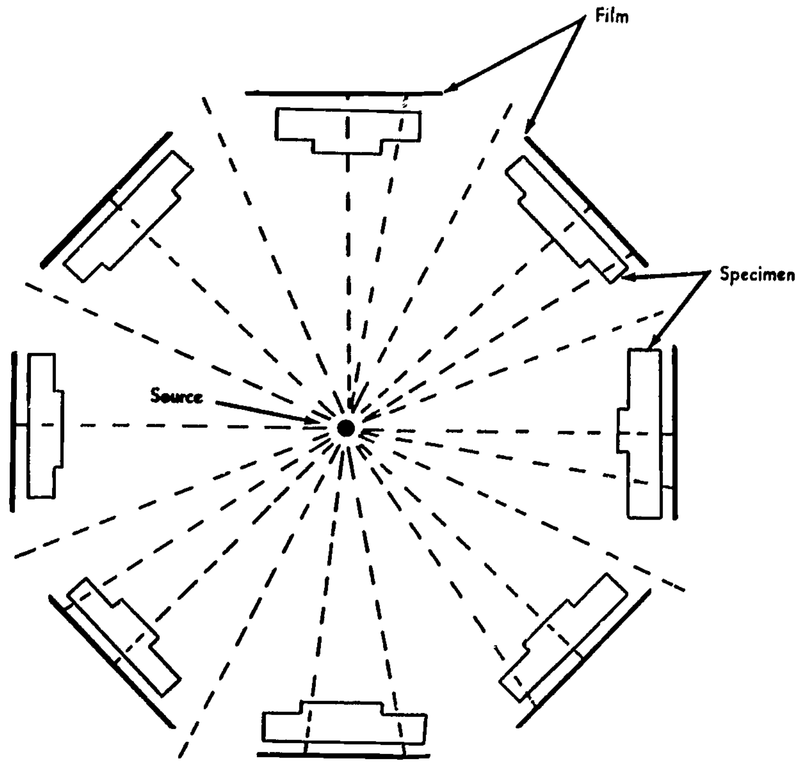


Figure 11.14.—Panoramic Exposure Arrangement.

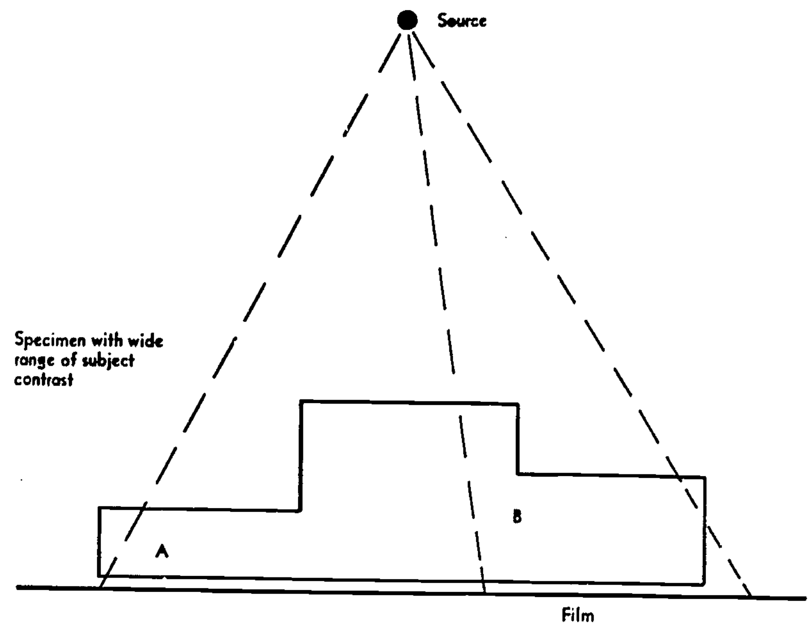


Figure 11.15.—Multiple Exposure or Multiple Film Technique.

11–4.3 *High Radiographic Contrast.* When excessive radiographic contrast is apparent, determine whether high specimen contrast or high film contrast is the cause. The cause of the first condition is usually a specimen thickness range is too great for the quality of radiation desired. This may be corrected by increasing the radiation energy (kev or mev). High film contrast is corrected by using film of lower contrast characteristics.

11–4.4 *Low Radiographic Contrast.* Low radiographic contrast is caused by (1) low subject contrast, (2) low film contrast, and/or

(3) underdevelopment. The first is caused by radiation which is too penetrating for the thickness range of the specimen and may be corrected by reducing the radiation energy (kev or mev). The second, low film contrast, can be corrected by substituting film of higher contrast characteristic. Underdevelopment is a matter of too short a development time, too cold a developer solution or a developer of too low chemical activity. Appropriate corrections should be made if these conditions are not correct.

11–4.5 *Poor Definition*. Radiographs with poor definition will not reveal detail possible within abilities of the process. This condition may be caused by several factors including (1) geometric exposure factors, (2) poor contact between film and intensifying screens, (3) graininess or fluorescent intensifying screens, (4) graininess of film. In the conditions of geometric factors excessive object-film distance can be corrected by decreasing the distance between the object and film or, if this is impossible, by increasing the focus-film distance. The second exposure problem results from using too large a radiation source size and may be corrected by using a smaller source size or by increasing the distance to the specimen. (Source size means the actual shape emanating the radiation whether it is the X-ray focal spot or a gamma ray source dimension.)

Film holders should be checked to see that contact between the film and screen is uniform over the entire area. Graininess caused by fluorescent intensifying screens is corrected by changing to lead foil screens. Graininess of film is reduced by using a finer grain radiographic film.

11–4.6 *Fog*. Films can develop fog from several possible exposures to light or radiation. First, it should be determined that the film has not received excessive exposure to light from leaks through walls or poor safelight filters. Next, film in storage should be checked for excessive exposure to radiation, heat, humidity, and harmful vapors and gases. Finally, the film processing procedure should be reviewed to eliminate overdevelopment and incorrectly mixed or contaminated solutions.

11–4.7 *Streaks*. Streaks are discussed elsewhere in connection with a description of the film processing. Streaks result when (1) film hangers are contaminated, (2) the film is improperly agitated, or (3) inspection of film allows developer to flow across the film before fixation. During the drying process, streaks and water spots may be eliminated by use of a wetting agent in the final water rinse before drying.

11–4.8 *Yellow Stain*. Yellow stains commonly result from (1) prolonged development in old, oxidized developer, (2) the omission of a stop bath or rinsing, and (3) improper fixation. In the first instance it is necessary to replace the developer solution. Proper stop bath and rinsing procedures will alleviate the second cause and the replacement of the fixer solution will correct fixation stain problems.

11–4.9 *White Scum*. The presence of a milky-appearing fixer solution indicates that the solution was mixed too warm, has been mixed too rapidly, or that the developer has been carried over into the fixer solution. Each condition can be readily avoided once it has been discovered.

11–4.10 *Physical Damage to Film Emulsion*. Puckered or net-like film surfaces, known as reticulation, result from sudden extreme temperature changes during processing. The importance of constant temperatures has already been stressed.

Another type of physical damage to the film emulsion results when a warm or exhausted fixer solution is used. This type of damage, known as frilling (loosening of film emulsion from its base) can be corrected by a fresh supply of fixation chemical.

Excessive temperatures may cause the emulsion to slough off from the backing.

11–4.11 *Miscellaneous Problems*. There are various other conditions which lower the quality of radiographs, all having to do with improper technique. Crimp marks are the result of sharp bends being forced on the film while being inserted into cassettes or film holders. Pressure marks result from mechanical impact or pressure. Air bells can be eliminated by tapping the top bar of the film hanger against the tank when first immersed in the developer. Light spots are often caused by chemicals being splashed on the film before development. Foreign materials on or in intensifying screens, or between screens and film during exposure cause images which can be avoided by habits of cleanliness and care.

Chapter 12

Interpretation of Radiographs

Because of the varied materials and processes which are subject to testing by radiography, the interpretation of radiographs is not a matter that can be made a routine procedure. The many conditions under which radiographs are made make the interpretation of radiographs a difficult matter. The successful interpretation of radiographs requires an understanding of the general principles of radiography, knowledge of the materials being tested, and some practical experience in reading radiographs in order to relate the images of discontinuities to the serviceability of the specimen. Thus, there is no formula or routine which can be set up for the interpretation of radiographs.

12–1 Basic Concepts of Interpretation

Inspection by radiographic means is generally used to determine the presence of discontinuities in materials or parts and to inspect assemblies in which components may be missing or out of proper position. This inspection is done in order to determine whether to accept or reject the part. *It should be noted that the presence of some defects or flaws does not mean that an item cannot serve its intended purpose.* Therefore, the person who interprets radiographs must exercise some judgment as to the degree of imperfection or discontinuity that exists and whether the discontinuity or imperfection will prevent the item from being used or fulfilling its purpose.

12–1.1 *General Ideas About Interpretation.* If absolute perfection was the required level of quality for all materials and assemblies, then the interpretation of radiographs would be relatively easy. The person interpreting the radiograph would simply declare that the product or assembly was unacceptable if he found any kind of discontinuity, flaw, or defect. However, in most cases in industry something less than perfection is satisfactory for most products. Engineering design specifications will establish quality guidelines for radiography. The person interpreting radiographs will then be aware of the fact that he will be required to make judgments about the acceptability of discontinuities existing in the product being inspected. Thus, there is no single quality level applicable to all the great variety of products and materials that will be subject to radiographic inspection. Each quality level must be evaluated and interpreted as it is related to the serviceability of the item and its contribution to the effectiveness of the completed product.

12–1.2 *Acceptable Quality Levels.* The responsibility for establishing quality levels is the initial obligation of the engineering and scientific groups designing the product. In terms of such factors as static and dynamic stress, operating temperatures, corrosion, creep and fatigue, surface appearance, and many other factors, specifications must be established for the acceptability of discontinuities. In almost all cases the cost would be prohibitive if perfect finished materials and products were required.

Quality levels are for the purpose of establishing some sort of standard or norm for a particular job. If the end use of a product requires that it be perfect then the standard quality level should be established as such. However, if the end use of an item does not require perfection then upholding too high a standard will be inefficient and will handicap the manufacturing of the item. Obviously, holding to a quality level that is too high would be wasteful. Therefore, the quality level or norm should be in keeping with the *service requirements* of the article.

There are many borderline cases needing interpretation in radiography work. For example, small gas holes may be a defect which will not cause the rejection of an article. Sometimes it is necessary to determine the strength and serviceability of an article with mechanical tests to determine whether certain kinds of flaws or defects may be acceptable. When this is done, the interpreter will be able to make better decisions about the acceptability of products in which certain kinds of discontinuities or imperfections are seen on the radiograph. Such a procedure will allow serviceable parts to reach the assembly line and will help the production of the item to be more efficient. However, the radiographer should call to the attention of the manufacturer the borderline cases. In many instances the manufacturer may be able to eliminate the defect by altering some of his procedures. If the manufacturer does not know of the borderline cases, then he is unable to improve the quality of his product even though the product may be of an acceptable quality.

12–2 Specifications, Codes and Standards

12–2.1 *Specifications, Codes, and Reference Standards.* In many cases the manufacturer may use certain radiographic codes, references, or specifications as the standard toward which he aims to manufacture his products. The interpreter must familiarize himself with the standards and specifications in order to make proper judgments about the evaluation of manufacturers' products. The rules, specifications, or standards upon which the interpretation of radiographs is based may serve two functions: (1) they may serve as a guide for identifying types of discontinuities; or (2) they may specify or indicate acceptable and unacceptable soundness conditions for products. Standards that function as a guide for the identification of discontinuities are often of a pictorial nature. These may consist of a series of radiographs or reproductions of radiographs which show various types of discontinuities. Sometimes a description and a sketch of discontinuities are included.

Specifications and standards that set up acceptable quality levels are commonly called "acceptance standards." These are used to determine whether or not parts, materials, or products are acceptable on the basis of evaluation by radiographic means. Acceptance standards may be indicated pictorially or they may be in the form of written rules.

Some of the organizations that have adopted radiographic codes and reference radiographs or charts include:

American Society of Mechanical Engineers
American Society for Testing and Materials
American Petroleum Institute
U.S. Army Ordnance Department
U.S. Air Force
U.S. Navy
American Welding Society

Copies of the appropriate codes and reference material should be available to the person responsible for interpreting the film.

Many critical-system manufacturers set up their own radiographic standards. They may develop a general set of radiographs to serve as an overall guide for evaluating discontinuities. In some cases, general radiographs are inadequate and a set of radiographs referring to a specific casting or part may be required for proper interpretation. In many instances test reports are made available upon the testing of an actual part which has first been radiographed. This testing may be done under actual or simulated service conditions. After completing tests, a standard may be chosen and the least acceptable standard for a particular product or part is set up and all further manufactured castings or parts may be presumed to have a quality equal to or better than the one established as a minimum.

In many cases, as time passes and as castings or parts are put into use it may be found that the parts may not need to be as good as the standards first established. Then the quality level may be changed. On the other hand, it may be found that parts should be better than the standard first established and so the quality level may be raised.

12–2.2 *Specific Interpretations.* From the above it may be realized that the interpretation of radiographs may be a very difficult task involving to a great extent good judgment on the part of the interpreter. In a specific instance, however, interpretation may be a fairly easy job especially when a radiographic standard has been selected for a specific process. For example, one may consider the welding of one piece of steel to another in a situation where it may be desirable to have radiographic examination. The engineer or designer who recognizes the need for radiographic examination is familiar with the reason for the examination. He becomes the source of information for the radiographic interpreter for this particular weld. The interpreter should be able to secure a series of radiographs of welds of this type which are of different qualities and compare these radiographs with those taken of actual welds. By working with the engineer-designer, the interpreter would be able to select one or more radiographs as the standard which would indicate the least acceptable condition. All other radiographs then would be evaluated in terms of these reference radiographs.

The interpretation of a specific product may be concerned with a casting, a weld, the inspection of a radio tube, or various other kinds of products. In many cases the problem of interpretation is not a general problem so much as one peculiar to the particular company and the specific product. Thus, factors related to inspection standards must be developed by the company itself and the general reference standards set up by societies or groups may not be of particular value in a case such as this. The person doing the interpreting, therefore, must be reliable and assume proper responsibility for his interpretations. The manufacturer would need to depend upon the good judgment of the interpreter to assure that a product of proper quality would be reaching his consumers.

For the needs of this training program manual, the material presented will be limited to materials selected from ASME, ASTM, and API publications.

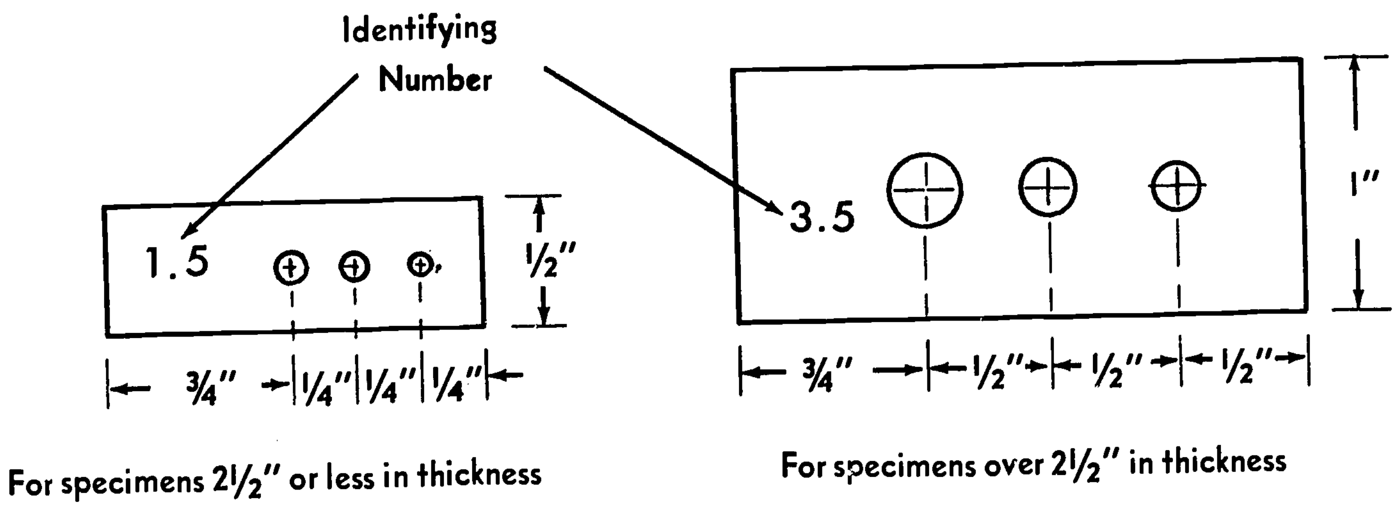
12–2.3 *ASME Code.* The ASME publishes a *Boiler and Pressure Vessel Code.* One section of the Code deals with unfired pressure vessels. This section includes standards for radiographic examination of welded joints and for spot-examination of welded joints. The main provisions of the radiographic code are as follows *:

1. Welds requiring complete radiographic examination will be examined over their entire length by the X-ray or gamma-ray method of radiography.

2. For butt-welded joints, weld ripples or surface irregularities, inside and outside, shall be removed by any suitable mechanical means so that radiographic contrast due to these irregularities will not mask defects.

3. Welds shall be radiographed with a technique which will indicate the size of defects

*Extracted from the 1965 edition of the ASME *Boiler and Pressure Vessel Code.* Section 8: Unfired Pressure Vessels. (With permission of the publisher, The American Society of Mechanical Engineers, New York.)



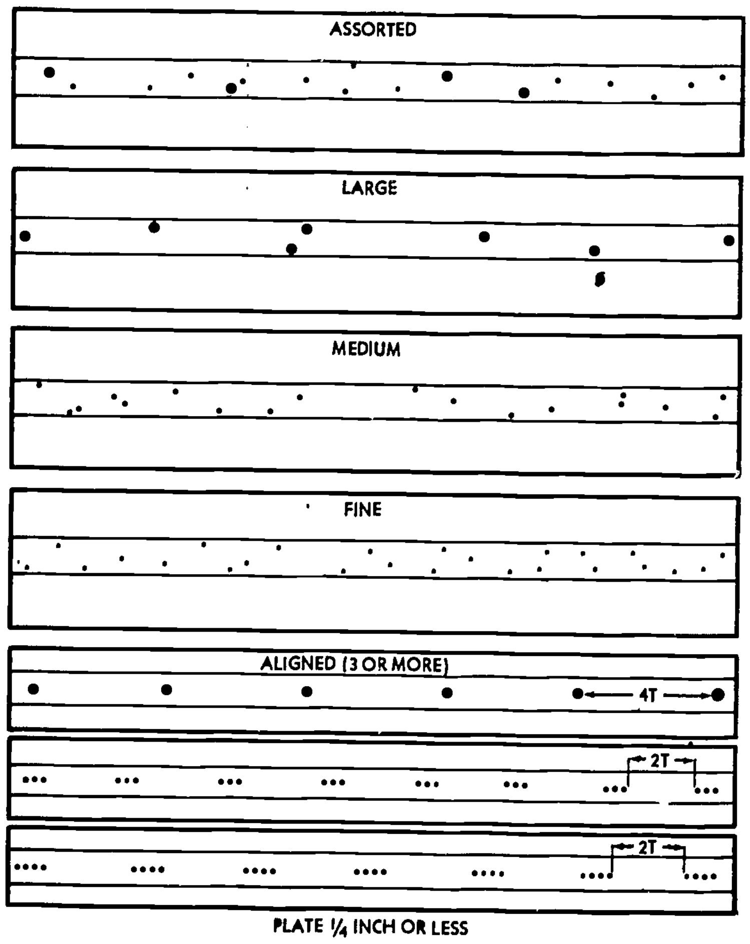
Note 1. The penetrameter shall consist of material substantially the same as that of the specimens under examination.

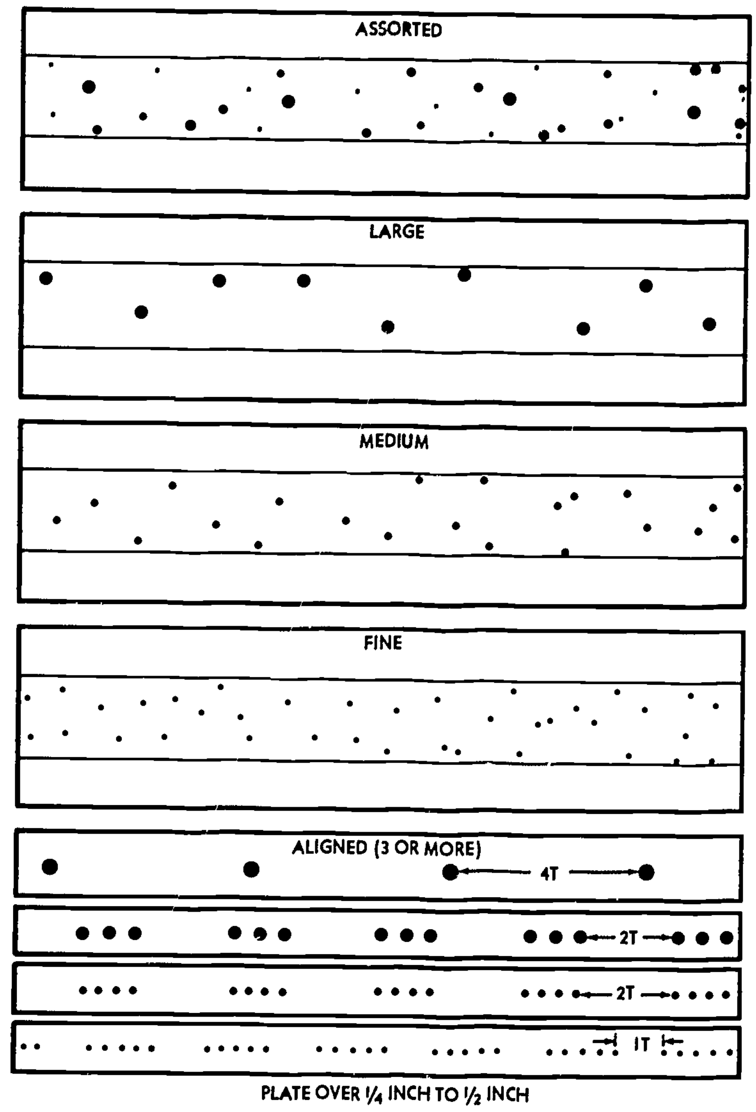
Note 2. The thickness of the penetrameter shall be not more than 2 percent of the thickness of the specimen.

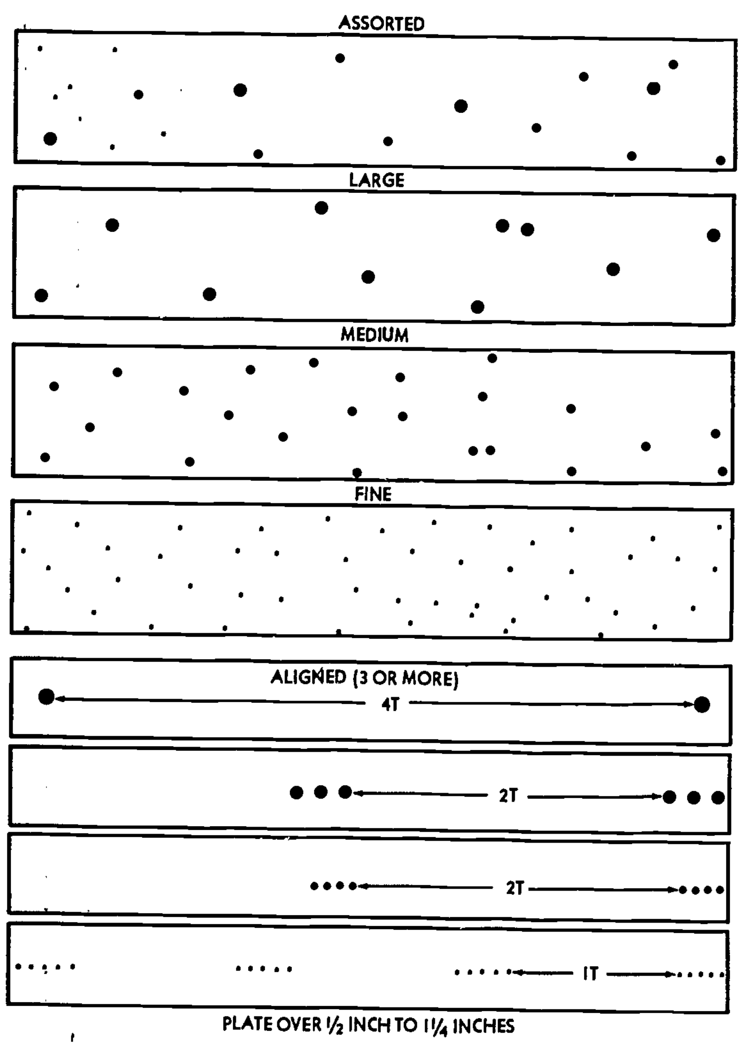
Note 3. The diameter of holes (left to right) shall be four, three, and two times the thickness of the penetrameter, but not less than 1/16 inch.

Note 4. The identifying number shall consist of lead figures cemented to the penetrameter; the number should indicate to two figures, the minimum thickness of the specimen for which the penetrameter may be used.

FIGURE 12.1.—ASME Boiler Construction Code Penetrameters.







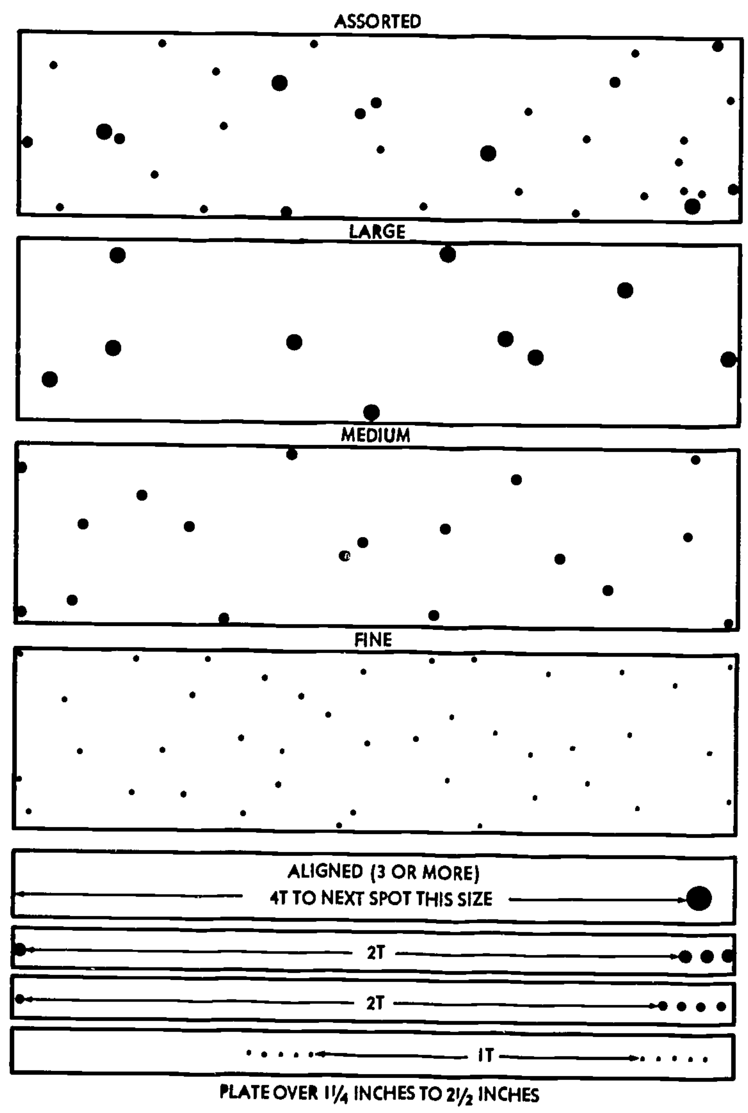


FIGURE 12.2—ASME Porosity Charts Showing Maximum Permissible Porosity in Welds.

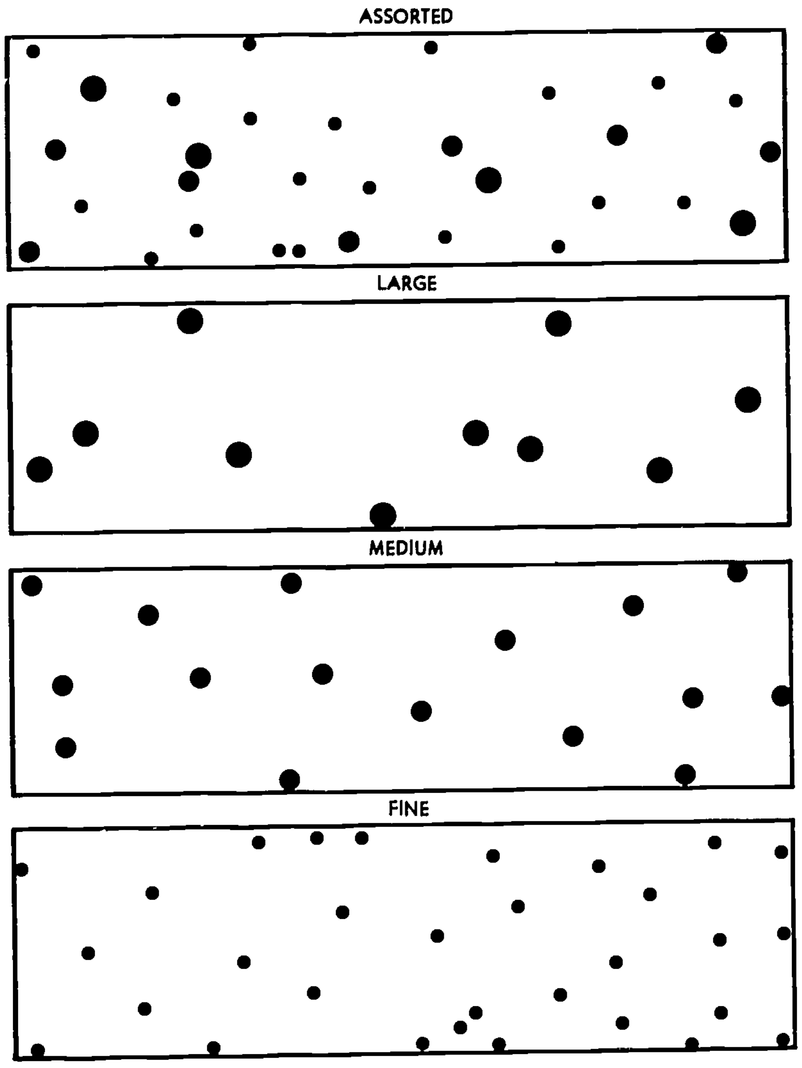


FIGURE 12.2—ASME Porosity Charts Showing Maximum Permissible Porosity in Welds. (Cont.)

having a thickness equal to and greater than 2 percent of the thickness of the base metal.

4. Penetrameters shall be used to check on the radiographic technique. (A description of the penetrameters to be used is given in Figure 12.1.)

5. During exposure, the film shall be as close to the surface of the weld as practicable. This distance should not be greater than one inch. If s is the distance from the radiation side of the weld to the source of radiation and if f is the distance from the radiation side of the weld to the film, then the ratio s/f should be 7 to 1 or greater. If the ratio is less than 7 to 1, the manufacturer should satisfy the inspector that the technique is adequate. When the ratio s/f is less than 7 to 1, the ratio shall be clearly indicated on each film or attached thereto.

6. Penetrameters are usually placed on the radiation side of the joint. They may be placed on the film side if the manufacturer can satisfy the inspector that the technique is adequate.

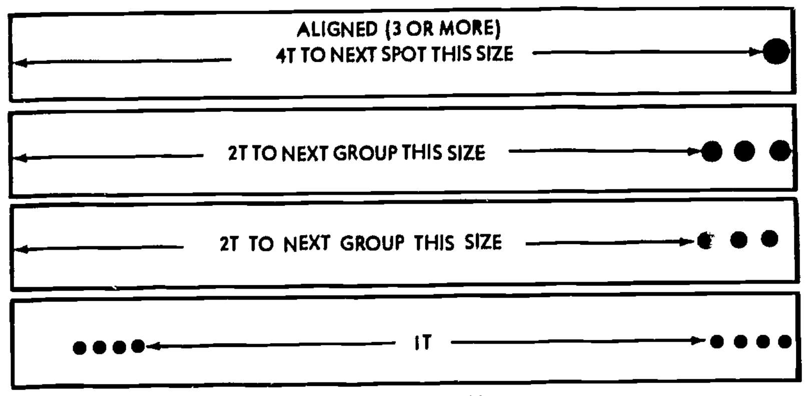


FIGURE 12.2—ASME Porosity Charts Showing Maximum Permissible Porosity in Welds. (Cont.)

7. When a complete circumference is radiographed with a single exposure, four uniformly spaced penetrameters shall be used.

8. Radiographs should be free from excessive mechanical processing defects which would interfere with proper identification of the radiograph.

9. Identification markers whose images appear on the film shall be placed next to the weld and their locations accurately and permanently marked on an outside surface near the weld. This serves to locate a defect appearing on a radiograph.

10. The job number, the vessel, the seam, and the manufacturer's name or symbol shall be plainly indicated on each film.

11. Radiographs shall be submitted to the inspector with any information about technique which he may request.

12. Sections of weld shown by radiography to have any of the following types of imperfections shall be unacceptable and shall be repaired as provided for in the Code.

(a) Any type of crack or zone of incomplete fusion or penetration
(b) Any elongated slag inclusion which has a length greater than ¼ inch for T up to ¾ inch, ⅓ T for T from ¾ inch to 2¼ inches, ¾ inch for T over 2¼ inches where T is thickness of the thinner plate being welded
(c) Any group of slag inclusions in line that have an aggregate length greater than T in a length of 12 T, except when the distance between successive imperfections exceeds 6 L, where L is the length of the longest imperfection in the group

(d) Porosity in excess of that shown as acceptable in the standards (See Figure 12.2.)

13. A complete set of radiographs for each job shall be retained by the manufacturer for at least five years.

The ASME code also includes rules for spot-examination of welded joints. Spot-examination may be used as a quality control measure. Such radiographs may be taken immediately after a welder or operator completes a unit of weld and they will show whether satisfactory procedures are being used. If the work is unsatisfactory, then corrections can be made if all radiographically disclosed defects are to be eliminated. A summary of ASME spot-examination rules follows:

1. Vessels or parts with butt-welded joints which are required to be spot-examined shall be spot-radiographed to the following minimum extent:

   (a) One spot shall be examined in the first 50 feet and for each additional 50 feet of welding in each vessel.

   (b) Such additional spots shall be selected so that each welding operator shall have welds examined.

   (c) Each spot-examination shall be made as soon as practicable after the completion of the increment of weld to be examined.

2. Standards for spot-radiographic examination include the following:

   (a) The minimum length of a spot-radiograph shall be 6 inches.

   (b) Spot-radiographs may be retained or discarded by the manufacturer after acceptance of the vessel by the inspector.

3. Acceptability of welds is judged as follows:

   (a) Welds in which radiographs show any type of crack or zone of incomplete penetration shall be unacceptable.

   (b) Welds in which radiographs show slag inclusions or cavities shall be unacceptable if the length of any such imperfection is greater than ⅔ T where T is the thickness of the thinner plate welded.

   (c) If several imperfections within the above limitations exist in a line, the welds are acceptable if the sum of the longest dimensions of all such imperfections is not more than T in a length of 6 T and if the longest imperfections are separated by at least 3 L of acceptable weld metal, where L is the length of the longest imperfection.

   (d) The maximum length of acceptable imperfections shall be ¾ inch. Imperfections shorter than ¼ inch shall be acceptable for any plate thickness.

   (e) Porosity is not a factor in the acceptability of welds not required to be fully radiographed.

4. Evaluation and retests

   (a) Spots acceptable under the above conditions mean that the entire weld length represented by the spot radiograph is acceptable.

   (b) When spots radiographed as above show unacceptable welding, then two additional spots shall be radiographed in the same weld unit away from the original spot.

   (c) If the two additional spots show welding meeting the above standards, the entire weld unit is acceptable. Defects shown by first spot-radiographs may be repaired or allowed to remain at the discretion of the inspector.

   (d) If either of the two additional spots shows welding not meeting minimum quality requirements, the entire weld unit is rejected. The entire weld may be removed and joint rewelded or the weld unit may be entirely radiographed and only the defective welding corrected.

   (e) Repair welding shall be performed using a qualified procedure and the rewelded joint shall be spot-radiographed at one location.

The above standards for radiographing and evaluating welded joints were adapted from the ASME *Boiler and Pressure Vessel Code*, section 8, 1965. For the complete standards refer to this publication. The standards described here are typical of standards adopted by some other groups.

12–2.4 *ASTM Radiographic Reference Materials.** The American Society for Testing and Materials has a committee on nondestructive tests. This committee has prepared reference materials concerning recommended practices for radiographic testing, controlling quality in radiographic testing, and radiographic references for various industrial processes and materials. For example, it has comparison radiographs for steel castings, aluminum and magnesium castings, steel welds, and steel castings for aerospace applications.

TABLE 12.1.—Classification of Steel Castings to be Used with Radiographic Standards.

CLASS	SERVICE
1	High-pressure or high-temperature service castings, or both (wall thickness less than 1 inch). Machinery castings [a] subject to high fatigue or impact stresses (wall thickness less than ½ inch).
2	High-pressure or high-temperature service castings, or both (wall thickness 1 inch or greater). Low-pressure service castings (wall thickness less than 1 inch). Machinery castings subject to high fatigue or impact stresses (wall thickness of ½ inch and greater).
3	Low-pressure service castings (wall thickness of 1 inch and over). Machinery castings subject to normal fatigue or impact stresses.
4	Structural castings [b] less than 3 inches in thickness and subject to high service stresses. Machinery castings subject to low impact stresses or vibration.
5	Structural castings 3 inches or more in thickness and subject to high service stresses.

[a] Machinery castings are dynamic parts or members in contact with working parts.
[b] Structural castings are construction parts for machinery castings.

The references suggest a classification of the service or use to be made of steel castings. Five levels of service are described and are numbered from one to five. Class 1 castings must meet the highest requirements while Class 5 castings must meet certain lower requirements. Also, seven types of defects are identified and labeled A to G in Table 12.2. Several reference plates are made for each defect showing different extents of the defect.

*Contents of Table 12.2 (ASTME 71–64) are published herein with the permission of the publisher, American Society for Testing and Materials, Philadelphia.

TABLE 12.2.—Classification of Defects in Steel Castings to be Used with Radiographic Standards.

GROUP	DEFECT
A	Gas and blowholes
B	Sand spots and inclusions
C	Internal shrinkage
D	Hot tears
E	Cracks
F	Unfused chaplets
G	Internal chills

For example, there are six reference radiographs showing gas and blowholes in steel castings. These are labeled A1 through A6. For Class 1 service, castings with gas or blowholes that match radiograph A1 are borderline castings. Castings with defects that match radiographs A2–A6 are unacceptable. For Class 3 service, casting with gas or blowholes that match radiographs A1 and A2 are acceptable, those that match radiograph A3 are borderline, and those that match radiographs A4–A6 are unacceptable. In other words, a casting with defects of a certain severity or extent may or may not be acceptable depending upon

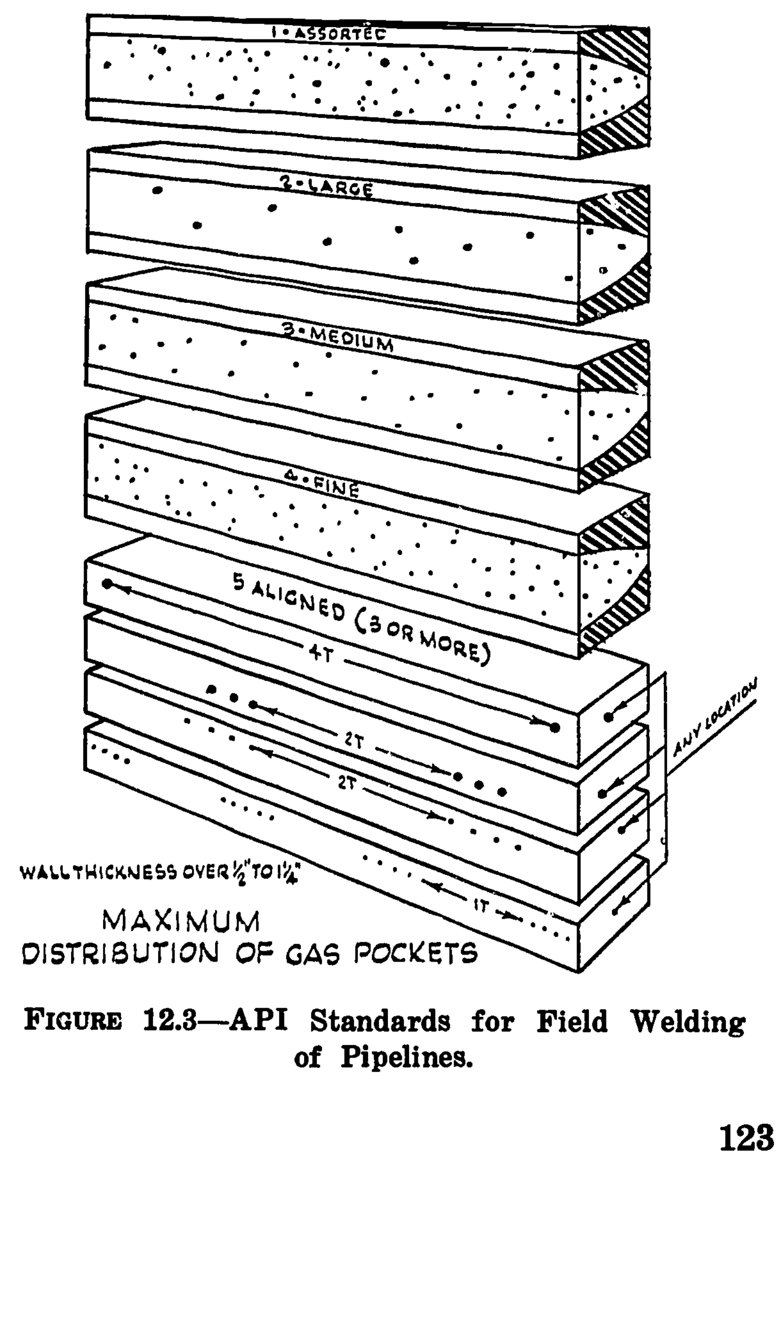


FIGURE 12.3—API Standards for Field Welding of Pipelines.

TABLE 12.3.—Radiographic Standards for Steel Castings.

PLATE NUMBER	CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5
GAS AND BLOWHOLES					
A1	BORDERLINE	Acceptable	Acceptable	Acceptable	Acceptable
A2	Unacceptable	BORDERLINE	Acceptable	Acceptable	Acceptable
A3	Unacceptable	Unacceptable	BORDERLINE	Acceptable	Acceptable
A4	Unacceptable	Unacceptable	Unacceptable	BORDERLINE	Acceptable
A5	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE
A6	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
SAND SPOTS AND INCLUSIONS					
B1	BORDERLINE	Acceptable	Acceptable	Acceptable	Acceptable
B2	Unacceptable	BORDERLINE	Acceptable	Acceptable	Acceptable
B3	Unacceptable	Unacceptable	BORDERLINE	Acceptable	Acceptable
B4	Unacceptable	Unacceptable	Unacceptable	BORDERLINE	Acceptable
B5	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE
B6	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
INTERNAL SHRINKAGE					
C1	BORDERLINE	Acceptable	Acceptable	Acceptable	Acceptable
C2	Unacceptable	BORDERLINE	Acceptable	Acceptable	Acceptable
C3	Unacceptable	Unacceptable	BORDERLINE	Acceptable	Acceptable
C4	Unacceptable	Unacceptable	Unacceptable	BORDERLINE	Acceptable
C5	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE
C6	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
HOT TEARS					
D1	Unacceptable	Unacceptable	Unacceptable	BORDERLINE [a]	Acceptable
D2	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE [a]
D3	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
CRACKS					
E1	Unacceptable	Unacceptable	Unacceptable	BORDERLINE [a]	Acceptable
E2	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE [a]
E3	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
UNFUSED CHAPLETS					
F1	Unacceptable	BORDERLINE	Acceptable	Acceptable	Acceptable
F2	Unacceptable	Unacceptable	BORDERLINE	Acceptable	Acceptable
F3	Unacceptable	Unacceptable	Unacceptable	BORDERLINE	Acceptable
INTERNAL CHILLS					
G1	Unacceptable	Unacceptable	BORDERLINE	Acceptable	Acceptable
G2	Unacceptable	Unacceptable	Unacceptable	BORDERLINE	Acceptable
G3	Unacceptable	Unacceptable	Unacceptable	Unacceptable	BORDERLINE
G4	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable

[a] Acceptable only when the angle between the defect and the direction of the principal stress is not greater than 20 degrees.

the service conditions. By making use of this comparison set of radiographs showing seven types of defects and up to six levels of severity, quality for steel castings may be rather specifically described (see ASTM *Book of Standards*, 1961, Part 3). (Table 12.3)

12–2.5 *API Standards.* The American Petroleum Institute uses sketches and measurements to describe the severity of defects in pipeline welding. For example, they have adopted specifications for field welding of pipelines. These include a chart showing the maximum distribution of gas pockets allowed in a field weld. The maximum distribution of fine, medium, large and assorted gas pockets is shown in a sketch. If the radiograph of a weld shows more gas pockets than are shown on the sketch, then the weld is rejected. Also shown are acceptable conditions for gas pockets that are aligned. (Figure 12.3)

12–3 Radiographic Sensitivity

A basic concern of the radiographer is securing radiographs that reveal small defects of discontinuities in the material under inspection. The term "radiographic sensitivity" usually refers to the ability of a radiographic procedure to detect discontinuities. Because the size, shape, and nature of discontinuities vary so greatly it is not possible to measure sensitivity specifically in terms of defect or discontinuity detection. In practice, sensitivity is specified as the ratio of the smallest thickness difference visible on the radiograph to the thickness of the material being examined. This may be expressed as a percentage.

12–3.1 *Percentage Sensitivity.* Sensitivity may be expressed as a ratio:

$$\text{Percentage Sensitivity} = \frac{s}{t} \times 100$$

where:

s = smallest detectable thickness difference

t = thickness of material being examined

Suppose the smallest detectable thickness difference in a radiograph of a piece of metal 2 inches thick was .04 inch. Then the radiographic sensitivity would be:

$$\text{Percentage Sensitivity} = \frac{.04}{2} \times 100 = 2\%$$

As a practical matter, this percentage is estimated by using a device known as a penetrameter which is placed on the object being radiographed.

12–3.2 *Penetrameters.* A *penetrameter* may consist of a small strip of the same material as the specimen and having a thickness which is in a definite ratio to the thickness of the specimen. For much routine work this ratio is arbitrarily set at *2 percent.* The radiographic procedure is considered satisfactory if the penetrameter edges and holes are clearly outlined on the radiograph. The penetrameter sensitivity then is said to be 2 percent or better (Figure 12.1).

Penetrameters also contain holes of various sizes. This aids in determining the quality of the radiographs even though a cavity in the material may not be visible while a hole in the penetrameter of the same diameter as the cavity may be visible. The reason for this is that the penetrameter has holes with sharp boundaries while a cavity may have less well defined boundaries. A penetrameter is therefore used to indicate the *quality* and *sensitivity of a radiograph and not to measure the size of a hole or cavity that may be detected.*

Some rules for radiographic examination state that radiographs will be used which will indicate the size of defect having a thickness equal to and greater than 2 percent of the base metal. To assure this level of quality, penetrameters of substantially the same material as the specimen must be used for each exposure and placed on the side of the specimen nearest the radiation source. They should be placed parallel and adjacent to the weld at one end of the exposed length, with the small holes at the outer end. The thickness of the penetrameter must not be more than 2 percent of the thickness of the specimen. Each penetrameter should contain three drilled holes two, three, and four times the penetrameter thickness, but in no case less than $1/16$ inch for X-rays and $3/32$ inch for gamma rays. The smallest hole should be distinguishable on the radiograph. The penetrameters shall carry numbers raised $3/32$ inch high which identify the material and indicate the minimum thickness of the specimen. These numbers should appear clearly on the radiograph.

12–4 Radiographs of Welds

Generally, defects in welds consist either of a void in the weld metal or an inclusion that has less density than the surrounding weld metal. Radiographs may show both internal and external discontinuities in welds. Internal discontinuities usually are the more serious, but external discontinuities may be serious and may not be detected simply by inspection of the surface. Not all discontinuities that appear on a radiograph make a weld unacceptable. To interpret a weld radiograph information about the welding procedure and the joint design should be available. This information will help in securing a better concept of how the weld should appear and in orienting the weld configurations to the radiograph.

Internal discontinuities described include: gas holes and porosity, slag inclusions, cracks and breaks, lack of penetration, lack of fusion, and tungsten inclusions. External or surface discontinuities described are as follows: undercutting, longitudinal grooves, excessive penetration, concavity at weld root, incompletely filled wild grooves, excessive reinforcement, overlap, irregularities at electrode change points, grinding marks, electrode spatter, and welds with backing rings.

12–4.1 *Gas Holes and Porosity*. Gas may be formed in fusion welding because of poor control of arc current, technique used, electrodes used, and quality of parent metal. The term "porosity" is used to describe gas inclusions that occur as rather spherical cavities in the weld metal. Gas inclusions may also occur as a tube-like cavity sometimes referred to as "wormholes." Porosity may occur as single cavities, in clusters of cavities, or randomly scattered cavities. Linear porosity may also occur along with incomplete penetration and is a series of cavities distributed along a line that runs lengthwise with the weld.

On a radiograph, porosity appears as round dark spots with rather sharp contours. They may be of varying sizes and distribution. Wormholes appear as dark rectangles if the axis of the cylinder is perpendicular to the radiation source beam, and as two concentric circles, one darker than the other, if the axis is parallel to the radiation beam. Linear porosity is recorded on radiographs as a series of round dark spots along a line with the weld.

ASME, ASTM, and other groups have set up standards, including reference radiographs and charts, for judging the acceptability of welds with porosity. Where a standard is specified, the work of the interpreter is easier. Pressure tanks for liquid or gas must have very high standards for porosity. For other types of usage porosity may not be important. Thus an interpreter of radiographs must secure much information about the use or service for materials that are welded.

12–4.2 *Weld Slag Inclusions*. Slags are usually oxides produced by arc welding. They serve to help take impurities from the molten metal and to form a layer over the weld to control cooling rates. Some slag may be trapped in the weld metal if it fails to remain molten long enough for the slag to rise to the surface. In welding requiring multiple passes, slag may be left on previous passes unless properly cleaned. Slag inclusions may be located along the edges of the weld metal deposits and run in a line along the length of the weld.

Since the oxides making up slags are usually of lower atomic weight than iron, they show up as dark irregular shapes on radiographs. Slag inclusions can occur singly, in clusters, or scattered randomly throughout a weld. They may also occur in a linear distribution. The images may have sharp, pointed ends and may be of variable density.

Slag lines appear along the edge of a weld as an irregular or continuous dark line on the radiograph. These are usually caused by insufficient cleaning between weld passes. Voids left between passes by irregular deposits of metal cause lines that have a similar radiographic appearance.

ASME and ASTM reference standards may be used to determine acceptability of welds with slag inclusions. As is the case with other discontinuities, service requirements determine the severity of slag inclusions which is acceptable.

12–4.3 *Cracks or Breaks*. Cracks in welds are usually produced by internal stresses caused by shrinkage of the cooling weld. Cracks may be along the weld seam or they may be across the weld seam. The latter cracks may extend into the parent metal. Cracks are generally wavy or zigzag lines and may have fine hairline cracks branching off from the main crack.

12–4 Radiographs of Welds

Generally, defects in welds consist either of a void in the weld metal or an inclusion that has less density than the surrounding weld metal. Radiographs may show both internal and external discontinuities in welds. Internal discontinuities usually are the more serious, but external discontinuities may be serious and may not be detected simply by inspection of the surface. Not all discontinuities that appear on a radiograph make a weld unacceptable. To interpret a weld radiograph information about the welding procedure and the joint design should be available. This information will help in securing a better concept of how the weld should appear and in orienting the weld configurations to the radiograph.

Internal discontinuities described include: gas holes and porosity, slag inclusions, cracks and breaks, lack of penetration, lack of fusion, and tungsten inclusions. External or surface discontinuities described are as follows: undercutting, longitudinal grooves, excessive penetration, concavity at weld root, incompletely filled wild grooves, excessive reinforcement, overlap, irregularities at electrode change points, grinding marks, electrode spatter, and welds with backing rings.

12–4.1 *Gas Holes and Porosity*. Gas may be formed in fusion welding because of poor control of arc current, technique used, electrodes used, and quality of parent metal. The term "porosity" is used to describe gas inclusions that occur as rather spherical cavities in the weld metal. Gas inclusions may also occur as a tube-like cavity sometimes referred to as "wormholes." Porosity may occur as single cavities, in clusters of cavities, or randomly scattered cavities. Linear porosity may also occur along with incomplete penetration and is a series of cavities distributed along a line that runs lengthwise with the weld.

On a radiograph, porosity appears as round dark spots with rather sharp contours. They may be of varying sizes and distribution. Wormholes appear as dark rectangles if the axis of the cylinder is perpendicular to the radiation source beam, and as two concentric circles, one darker than the other, if the axis is parallel to the radiation beam. Linear porosity is recorded on radiographs as a series of round dark spots along a line with the weld.

ASME, ASTM, and other groups have set up standards, including reference radiographs and charts, for judging the acceptability of welds with porosity. Where a standard is specified, the work of the interpreter is easier. Pressure tanks for liquid or gas must have very high standards for porosity. For other types of usage porosity may not be important. Thus an interpreter of radiographs must secure much information about the use or service for materials that are welded.

12–4.2 *Weld Slag Inclusions*. Slags are usually oxides produced by arc welding. They serve to help take impurities from the molten metal and to form a layer over the weld to control cooling rates. Some slag may be trapped in the weld metal if it fails to remain molten long enough for the slag to rise to the surface. In welding requiring multiple passes, slag may be left on previous passes unless properly cleaned. Slag inclusions may be located along the edges of the weld metal deposits and run in a line along the length of the weld.

Since the oxides making up slags are usually of lower atomic weight than iron, they show up as dark irregular shapes on radiographs. Slag inclusions can occur singly, in clusters, or scattered randomly throughout a weld. They may also occur in a linear distribution. The images may have sharp, pointed ends and may be of variable density.

Slag lines appear along the edge of a weld as an irregular or continuous dark line on the radiograph. These are usually caused by insufficient cleaning between weld passes. Voids left between passes by irregular deposits of metal cause lines that have a similar radiographic appearance.

ASME and ASTM reference standards may be used to determine acceptability of welds with slag inclusions. As is the case with other discontinuities, service requirements determine the severity of slag inclusions which is acceptable.

12–4.3 *Cracks or Breaks*. Cracks in welds are usually produced by internal stresses caused by shrinkage of the cooling weld. Cracks may be along the weld seam or they may be across the weld seam. The latter cracks may extend into the parent metal. Cracks are generally wavy or zigzag lines and may have fine hairline cracks branching off from the main crack.

The radiographic image of a crack defect is a dark narrow line that is usually irregular. If the plane of the crack is in line with the radiation beam, its image will be a fairly distinct line. If the plane is not exactly in line with the radiation beam, a faint dark linear shadow may result. In this case additional radiographs should be taken at other angles.

Since cracks are a very serious weld defect, additional radiographs should be made when in doubt. Fine grain films may be used, the angle of the radiation beam changed, and perhaps other kinds of non-destructive testing may be used to supplement the radiographs.

By most standards cracks of any kind are unacceptable. Certainly on welds that must withstand pressures or tensions, cracks are a very serious defect that could make a weld unacceptable.

12–4.4 *Lack of Penetration.* This defect occurs at the root opening at the bottom of the welding groove or at the center of the weld for two-sided welding. It is caused by failure of the root pass to fuse properly with the parent metal at the root. Root openings are used to permit penetration of fusion to the bottom of the weld opening or groove. Often tack welds are used to prevent movement of pieces being welded. Then one or more passes are made with beads being laid over each other until the groove is filled.

If the root opening is too small for the weld rod and the current being used, incomplete penetration may result. Sometimes poor beveling or preparation of the weld groove can cause voids at the root area of the weld. Where possible a cover pass on the back side of the weld may fill such a void.

The radiographic image of such a void appears as a straight dark line in the center of the weld. The width may vary from a thin sharp line to a broad diffused line. Slag inclusions and gas holes may be found in connection with a lack of penetration void. These may cause enlargements of the primary dark line or may cause it to be accompanied by a sort of dotted line. Slag inclusions may cause the primary line to appear broad and irregular.

Sometimes, lack of penetration may show on a radiograph as a very narrow dark line. The narrowness may be due to a drawing together of the plates being welded and the lack of penetration may be very severe.

The ASME standard for welded pressure vessels states that any weld shown by radiography to have a zone of incomplete fusion or penetration is unacceptable and must be repaired. Again, depending upon the service requirements of the product, lack of penetration is usually a serious defect.

12–4.5 *Lack of Fusion.* Because of lack of heat or improper cleaning of the fusion face of a weld bevel, the weld metal may not fuse properly with the parent metal. They may remain separated by a thin layer of oxide which causes a discontinuity along the wall of the bevel.

The radiograph of a lack of fusion shows a very thin straight dark line parallel to and on one side of the weld image. Where there is doubt, additional radiographs should be made with the radiation beam parallel to the bevel face. This will increase the possibility of the defect appearing on the radiograph. A lack-of-fusion line is usually straight on one side and irregular on the other.

This is a serious weld defect and, depending upon service conditions, may cause a weld to be unacceptable.

12–4.6 *Tungsten Inclusions.* If the tungsten electrode used in arc welding contacts the weld metal some small particles or splinters of the tungsten wire may become trapped in the metal that is deposited. Since tungsten has a very high melting point no fusion will occur. Tungsten has a higher atomic weight than iron and so has a higher radiation absorption than iron at the energies usually required for radiography. Therefore, tungsten inclusions will appear on a radiograph as light marks instead of dark ones.

Tungsten inclusions may appear as single light spots or as clusters of small light spots. The spots are usually irregular in shape, but sometimes a rectangular-shaped light spot will appear.

12–4.7 *External Discontinuities.* Various kinds of surface irregularities may cause density variations on a radiograph. As an aid in interpretation these should, where possible, be removed before radiographing the weld. Where it is impossible to remove surface irregularities, they should be considered during interpretation to avoid mistaking their images for internal defects.

A common surface defect is undercutting which is caused by melting of the upper edge of the beveled weld face. When insufficient weld metal is deposited to fill the groove the parent metal may be reduced in thickness at the point of fusion on the edge of the weld bead. This results in a radiographic image showing a dark line of varying width and density. The darkness or density of the line indicates the depth of the undercut. The density and sharpness of the image will help in judging the severity of the condition. In two-side welding, undercutting may occur on the back side of the weld, so this condition should be identified where possible.

In multipass welds on horizontal positions a smooth top surface may not be produced if longitudinal grooves form in the surface of the weld metal paralleling the weld seam. These grooves may produce dark lines on a radiograph. These lines have diffused edges which should not be mistaken for slag lines which are narrow and more sharply defined. These dark lines are seldom straight, and they are parallel to the weld seam.

Sometimes molten metal may run through the root of the weld groove and be deposited on the back side of the weld. This may be caused by a wide root opening or by the unusually high temperature of the molten metal. Drops of excess metal may form. This adds to the thickness of the weld reinforcement and causes a lowered image density in the center of the weld image. Round light spots may correspond to hanging drops of metal on the back side of the weld.

In overhead welding especially, there may be concavity at the root of the weld. Since this means less weld metal at the root, the radiographic image will be a dark line down the center of the weld. The line is broader and does not have sharp boundaries as do lack-of-penetration lines.

Weld grooves not completely filled appear as dark lines on a radiograph. If the lack of fill occurs at the bevel, the dark line will be located on one edge of the weld image and will have a sharp border on one side and an irregular border on the other side. If the incomplete fill occurs in the center of the weld, the dark line will be rather wide and have diffused borders.

Weld grooves may be overfilled due to an excessive number of passes or an inadequate arc current. The overfill is referred to as "weld reinforcement." If the reinforcement is too high, the weld radiograph will show a lighter line down the weld seam. There will be a sharp change in image density where the reinforcement meets the parent metal.

Sometimes when excess metal is deposited on a final pass, the excess metal may overlap the parent metal. There may be a lack of fusion at the edge of the reinforcement. While there will be a sharp change in image density between reinforcement and parent metal, the edge of the reinforcement image is usually irregular.

Reinforcement thickness may be reduced on a cover pass at the end of a bead laid with an electrode which is to be changed. Increased thickness may occur at the point where the new electrode is started. The extra reinforcement forms a crescent shape with its convex side nearest the reduced reinforcement area left by the first electrode. The radiograph shows a crescent shaped image of less density because of extra metal.

Weld reinforcements may not be ground out completely smoothly. In this case image will show irregular densities often with sharp borders. Improper electrodes or long arcs may cause drops of molten metal to spatter about the weld seam. These stick to the parent metal and appear as light round spots on a radiograph.

In pipe welding it is often impossible to make a cover pass at the root of the weld. Frequently a backing ring is inserted before welding and is then left inside the pipe. This ring is partially fused to the weld metal on the root pass. The ring produces a well defined image on the radiograph. This is a light band across the radiograph. The weld reinforcement shows up as a still lighter line across this band. Many of the usual weld discontinuities may still occur where backing rings are used. Slag entrapment may cause concavity at the root during the root pass. Also, lack of penetration can occur.

12–5 Radiographs of Castings

A casting is usually defined as a piece of metal formed in a mold which is a shaped cavity prepared to receive molten metal. There is a variety of types of molds and ways of introducing molten metal into the mold. The radiographer to be of most use to a foundry or the casting industry should become acquainted with their manufacturing methods.

Radiography may serve the casting industry in two ways. It may be used to inspect castings to control quality of production. Internal defects may be found before more costly machining operations are started. Also, defects not uncovered by machining may be detected before there are service failures. Also, radiography may be used as an aid in casting design. Pilot castings may be examined to develop good foundry techniques related to chilling, gating systems, risering, and venting.

The thoroughness with which a casting should be radiographed depends upon the design and use to which the casting will be put. Castings that must undergo high stresses and which may not have a high safety factor may require extensive radiographing. Castings not subjected to high stresses may require only a minimum of radiography necessary to detect the most severe defects.

Some of the common defects that appear on radiographs are described in this section. Some of these defects are found in ferrous castings and some are peculiar to light metal castings and alloy castings. Those described are gas holes, porosity, shrinkage cavities, inclusions, cold shuts, cracks, core shift, hot tears, segregation, microshrinkage, and surface irregularities.

12–5.1 *Gas Holes*. The entrapment of gas, as molten metal cools in a mold, causes the defect or discontinuity in castings known as "gas holes." The gas may have been dissolved in the metal; it may arise from the mold; or it may have been trapped as the molten metal was "gated" into the mold. The holes may occur singly, in cluster, or randomly distributed throughout the casting. Gas holes appear on the radiograph as dark areas with smooth borders.

Sometimes gas holes may be machined off a casting. Therefore the interpreter should have information related to machining when evaluations are made. Sometimes if a cavity is revealed by machining, welding or more machining may make the casting acceptable.

In evaluating the effects of gas holes found by radiography, the end use of the product must be considered. For example: the part may be required to hold liquid, it may be a moving part, or it may be highly stressed. The effects of gas holes on the part as it fulfills its functions must be studied. The designer or engineer may have blueprints showing points of stress. The safety factors in the design may be considered. The exact service requirements should be known and used in a reasonable interpretation of radiographs showing defects or discontinuities such as gas holes.

Generally, it is known that gas holes weaken a part. The amount of weakening is based on the size of the gas hole or holes in relation to the cross section of the part in which they exist. Gas holes grouped closely may be considered as one larger hole. Gas holes may be aligned in such a way as to represent a "propagating" discontinuity. This is a serious defect which renders a part unacceptable. This is especially true if the part is subject to repeated vibration or shock stresses. Isolated holes may not be too important with regard to strength. However, aligned gas holes may present problems in evaluation even when reference standards are available.

12–5.2. *Porosity*. A generally porous or spongy condition in a casting is called "porosity." Two kinds of porosity have been identified. These are caused by gas (gas porosity) and by shrinkage (shrinkage porosity). Gas porosity is caused by the release of gas from the cooling metal and from green sand molds. Inclusion of various kinds of impurities as well as high temperatures may also account for gas in a casting. Gas porosity appears on a radiograph as very small round dark spots. These may vary from very minute spots closely bunched to single large round spots. Sometimes in aluminum castings the voids in gas porosity may be elongated instead of round.

Shrinkage porosity is usually caused by lack of metal. As a casting cools, it takes metal from the risers. If the risers should cool first, no molten metal would be available to keep the mold cavity completely filled. Thus, some or all of the casting may have some shrink porosity. Shrink porosity appears as a dark highly irregularly shaped image on a radiograph. It may be easily distinguished from gas porosity.

Gas porosity of a minor severity does not greatly affect the strength of a casting. The effect may be determined by testing a series of castings containing porosity of various degrees of severity. If radiographs are first made of these test castings they may help the radiograph interpreter evaluate porosity in castings. Also the findings may help the manufacturer adjust his casting techniques.

12–5.3 *Shrinkage Cavities*. Shrinkage cavities are caused by an insufficient amount of molten metal when the casting cools. They are usually found along with shrinkage porosity. Early setting of metal in the risers may cause a part of the casting to receive insufficient metal as the part sets. Shrinkage cavities appear on a radiograph as dark irregularly shaped spots. These may vary considerably in cross section areas, depending upon the size of the casting.

Shrinkage cavities and gas holes affect the serviceability of a casting in much the same way. Since the cavity has sharp boundaries it is a propagating type of discontinuity. This is a serious defect, especially for castings that must withstand vibrations and shock loadings.

12–5.4 *Inclusions*. Inclusion is a term applied to sand, oxide, slag, or any other foreign material in a casting. Inclusions may appear as light or dark spots on a radiograph depending upon the relative densities of the inclusion and the base metal. If an inclusion is denser than the base metal it will appear as a light spot on a radiograph. In some cases inclusions do not harm the serviceability of a casting. In other cases it may render an item unusable.

12–5.5 *Misruns*. A misrun occurs when molten metal fails to fill the mold completely. It may be a minor void which is externally apparent. Sometimes, however, a minor appearing misrun connects to a deeper cavity which may be seen on a radiograph. Misruns, being voids, appear on a radiograph as dark areas with rather well defined borders. In large, costly castings, misruns may be repaired by welding or other procedures where the service requirements will allow.

12–5.6 *Cold Shuts*. Sometimes streams of molten metal entering a mold are split by cores or chaplets and come together again. When the streams of metal set to such an extent that they do not fuse into each other upon meetings, a cold shut results. This may happen with magnesium, for example, because of the narrow range of temperatures at which the metal flows without oxidizing or setting. Cold shuts appear as rather well defined dark lines on a radiograph. Sometimes they are difficult to see. Cold shuts may affect the serviceability of parts which have highly stressed applications. For parts that are not under stress some degree of this defect may be allowed. Cold shuts may be evaluated in a manner similar to cracks.

12–5.7 *Cracks*. Cracks may be caused by stresses in cooling of the casting, incorrect design of the casting, or by rough handling of the mold. A crack usually makes a casting unacceptable, unless it can be repaired by welding. This is usually too costly except in large castings. On a radiograph, cracks appear as dark, irregular, intermittent, or continuous lines. If the plane of the crack is parallel to the radiation beam, the lines are darker and more easily seen. Usually, however, a crack is very irregular and only a small part will be aligned with any given radiation beam. Therefore, exposures from several positions may be necessary to determine the extent of a crack or even to properly locate one. Other non-destructive methods should be used to supplement radiography in detecting cracks.

12–5.8 *Core Shift*. Some castings are made by inserting a core in the mold to produce a void in the casting. If the core is not firmly fixed in the mold, it may shift when the molten metal is poured. A shift of the core is easily seen on a radiograph since the void left by the core appears as a dark well defined area. Evaluation of core shifts should consider the design allowances for machining of wall thickness.

12–5.9 *Hot Tears*. As metal cools it contracts. Sometimes, because of the shape and because of the rigidity of the mold, stresses are set up in the cooling metal. If these stresses exceed the strength of the metal, tears or cracks may appear in the still hot metal. These are likely to occur at places where a thin section joins a thicker section of the casting. Impurities may cause weak spots and contribute to the tear. Tears appear on a radiograph as dark lines that are very ragged and may have a number of branches of varying densities.

12–5.10 *Segregation*. When certain alloys are used for castings, the constituent metals may tend to separate in spots. This separation will show up as light and dark blotches on a radiograph. Usually, castings with segregation are rejected, except when relatively small areas show this condition.

12–5.11 *Microshrinkage*. Magnesium castings sometimes have a kind of porosity referred to as "microshrinkage." The radiographic image of microshrinkage is usually darker and sharper than shrinkage porosity in aluminum. The image is one of fuzzy or feathery streaks that outline a definite area.

12–5.12 *Surface Irregularities*. Surface irregularities should be studied so that the interpreter can distinguish them from internal discontinuities of various kinds. A surface irregularity may or may not be considered a defect. However, since they appear on radiographs the casting should be visually inspected and surface irregularities noted.

Two common types of surface irregularities are surface pits and excess surface metal. Surface pits usually appear as rather diffused dark spots without well defined borders. Their radiographic image appears similar to inclusions. Some surface irregularities are sharply defined and may be difficult to distinguish from inclusions or blowholes on a radiograph.

Excess surface metal appears as light areas corresponding to the dimensions of the excess metal. This condition is usually rather easy to identify because of the light density of the image.

Part IV

Regulations and Procedures

Through ignorance, carelessness, or disregard for safety and, in some cases, equipment failures, there has been a long series of unfortunate and unnecessary human overexposures to radiation. In many incidents the cause was directly attributable to failure on the part of a responsible technician.

An effort to eliminate this situation has led government agencies to prepare regulatory control measures. These agencies have adequate authority to enforce compliance.

Rather than viewing these as policing and enforcement matters, the radiographer could have a better working perspective by accepting the regulations as safety guidelines. Some of the Nation's leading authorities frequently review and revise the regulations. The revisions give due consideration to the technician's operating requirements.

It is advisable for the student to obtain and study, along with Chapter 13, a copy of the "AEC Licensing Guide—INDUSTRIAL RADIOGRAPHY" referred to on page 135.

Chapter 13

Government Licensing, Health, and Transportation Regulations for Isotope Radiography

13–1 The Authority for AEC Regulations

The Atomic Energy Commission (AEC) is the branch of the Federal government which is responsible for the atomic energy program. In addition to operating its facilities, the AEC regulates and licenses uses of selected nuclear materials. The powers of the AEC to establish regulations and grant licenses are pursuant to the Atomic Energy Act of 1954 (68 Stat. 919).

This chapter is concerned with the various government regulations which apply to the licensing, use, and transportation of radioactive materials in connection with industrial radiography operations.

All discussions, except those pertaining to transportation, are based on AEC regulations as published in the Code of Federal Regulations (CFR), Title 10, Chapter I, Parts 20, 30, and 34, which are the portions most pertinent to radiographic operations. The "AEC Licensing Guide for Industrial Radiography" supplements these regulations. (It is available from the Atomic Energy Commission.) This guide should be available to every radiographer studying this manual. Any person planning to apply for an isotope radiography license should use this guide in preparing the license application form and the supplementary records and as an aid in carrying out the required supplementary procedures. The discussions on transportation are based on federal transportation regulations. *These discussions are not official interpretations of federal regulations, and should not be taken as such.* They are simply illustrative and explanatory notes designed to acquaint the reader in a general way with the controls which are currently in effect.

In actual practice, the AEC sets standards for its operations and for licensees on the basis of its own operating and research experiences and the recommendations of the Federal Radiation Council (made up of the Secretaries of Defense, Commerce, Labor, and Health, Education, and Welfare plus the Chairman of AEC and others designated by the President) and the National Committee on Radiation Protection and Measurements (comprised of notable scientists, physicians, and government officials experienced in radiation). The National Committee cooperates closely with the International Committee on Radiological Protection.

Regulations and safety rules are drawn to limit personnel radiation exposures to a point far below danger levels and to afford acceptable protection for the general public of the United States.

13–2 Licensing and Policing Authority of States and Other "Bodies"

The Atomic Energy Act of 1954 was amended in 1959 to permit the AEC to enter into agreements with the governor of a State to allow the State to assume certain of the Commission's regulatory authority. This authority is specifically limited to byproduct, source, and special nuclear material in quantities not sufficient to form a critical mass.

States which have accepted these responsibilities from AEC are called "Agreement States." At this time there are several Agreement States. Other States are in the process of assuming such controls.

13–3 Requirements for a Specific License to Use Byproduct Materials for Radiography

Specific licenses to use byproduct materials are issued to named persons upon successful application to the appropriate agency. All persons who "manufacture, produce, transfer, receive, acquire, own, possess, use, import, or export" byproduct material must have such a license. The requirements for a license are summarized here and discussed in greater detail in sections which follow.

The first step for a specific license is filing an application form. (See Figures 13–1a, b.)

This form must be completed and submitted to the appropriate regulatory body.

There are general requirements which must be met before a radiography license will be issued. The first is that applications must be for a purpose authorized by the AEC Act. The second requirement is that the applicant's proposed equipment and facilities be adequate to protect health and minimize danger to life and property. Radiation protection standards are used to determine whether or not this condition is met. The third general requirement is that the applicant be thoroughly qualified by training and experience to use the byproduct material for the purpose requested and according to the safety measures required.

Applicants who will be using sealed sources in radiography must also meet the following additional specific requirements to be approved for licenses: (1) The applicant must show that he has an adequate program for training radiographers and radiographers' assistants. (The type of training program required is outlined later in this chapter.) (2) The applicant must indicate that rather detailed records showing the receipt, transfer, export, and disposal of byproduct materials will be kept and that these reports will be available for inspection. (3) The applicant must include satisfactory written operating and emergency procedures and an internal test and inspection system in his application. (4) Finally, it is specifically required that a description of the overall organizational structure of the proposed operation be submitted with the application. These requirements are elaborated upon later in this chapter.

When it has been determined that an application complies with licensing requirements, an appropriate license will be issued.

13–4 Conditions and Control of Licenses

The provisions of the AEC Act define violations of any of its licensing requirements as a crime punishable by fine and imprisonment. Such strong penalties are necessary because of the health consequences of violations. At any time that a violation occurs or appears imminent, the Commission may obtain an injunction or court order and take punitive action against the offender.

The regulations do not allow transfer of a license to another person, except with written permission. This permission is not given until the person to receive the license has fulfilled all the requirements for holding a license.

Each license issued by AEC includes an expiration date, at which time it becomes invalid. If and when a license becomes invalid all radiation work covered by the license must be suspended. However, licensees are permitted to apply for renewal of their licenses. Such applications should be filed and submitted at least 30 days before expiration of the old license. The old license will remain in effect so long as the renewal application is pending.

The revocation or suspension of a license may be done for two primary reasons: (1) the making of false statements in connection with or in the application for a license; (2) the discovery of conditions in violation of the terms of a license. In connection with the latter, the licensee will usually be given an opportunity and time to make whatever changes are necessary for compliance, with one exception—cases of willful violation.

The regulations grant the power to withhold or recall byproduct material from licensees when it is felt the latter are not equipped to carry out necessary safety precautions. Violation of safety and other regulations is also cause for the withholding or recalling of such materials.

The regulations provide that when the Commission enters into an agreement with a State, the licenses issued by the State will be recognized by the Commission within certain specified limits. These limits apply when an Agreement State license does not limit radiography to one address, but rather provides for field use at temporary job sites.

13–5 General Standards for Protection Against Radiation

It has been brought out that radiation can be safely used in production, research, and development applications. At the same time, it was made clear that rather rigid safety standards must be maintained for protection against radiation hazard. Regulations are designed to control the receipt, possession, use, and transfer of licensed material by licensees in such a manner as to prevent individuals from receiving radiation exposure in excess of the prescribed standards. These standards are considered adequate to safeguard the radiation

Form AEC-313R (9-62)	UNITED STATES ATOMIC ENERGY COMMISSION **APPLICATION FOR BYPRODUCT MATERIAL LICENSE— USE OF SEALED SOURCES IN RADIOGRAPHY**	Form approved Budget Bureau No 38-R137

SEE ATTACHED FORM AEC-313R INSTRUCTIONS—USE SUPPLEMENTAL SHEET WHERE NECESSARY
BE SURE ALL ITEMS ARE COMPLETED AND THAT ALL NECESSARY ATTACHMENTS ARE FURNISHED. IF ANY PORTION OF THE APPLICATION IS NOT APPLICABLE SPECIFICALLY SO STATE. DEFICIENT OR INCOMPLETE APPLICATIONS MAY BE RETURNED WITHOUT CONSIDERATION.

1(a) NAME AND ADDRESS OF APPLICANT	2. PREVIOUS LICENSE NUMBER(S) *(Indicate if application is for renewal or amendment of an existing byproduct material license.)*
1(b) APPLICANT IS: An individual ☐ A partnership ☐ A Corporation ☐ An Unincorporated Association ☐ Other ☐ If applicant is other than an individual, the applicable section on the reverse side must be completed.	3. LOCATION(S) WHERE SEALED SOURCES WILL BE USED AND/OR STORED *(If use will be made in states other than named in 1(a), they should be listed here.)*

4. SEALED SOURCES TO BE USED IN RADIOGRAPHY

BYPRODUCT MATERIAL *(Element and Mass No.)*	SOURCE MODEL NUMBER	NAME OF MANUFACTURER	MAXIMUM ACTIVITY PER SOURCE	NUMBER OF SOURCES
A	A	A.	A.	A.
B	B.	B.	B.	B.
C.	C.	C	C.	C.

5. RADIOGRAPHIC EXPOSURE DEVICES AND/OR STORAGE CONTAINERS TO BE USED WITH SOURCES LISTED ABOVE

MODEL NUMBER	NAME OF MANUFACTURER *(If custom made, attach complete design specification.)*
A	A.
B	B.
C	C.

6. THE FOLLOWING INFORMATION IS ATTACHED AS A PART OF THIS APPLICATION: *(Check appropriate blocks and attach information called for in the instructions with this form.)*

	Not Applicable	Attached	Previously Submitted
(a) Description of radiographic facilities (Instruction 6–a)	☐	☐	☐ on ____ (DATE)
(b) Description of radiation detection instruments to be used (Instruction 6–b)	☐	☐	☐ on ____ (DATE)
(c) Instrument calibration procedures (Instruction 6–c)	☐	☐	☐ on ____ (DATE)
(d) Personnel monitoring equipment (Instruction 6–d)	☐	☐	☐ on ____ (DATE)
(e) Operating and emergency procedures (Instruction 6–e)	☐	☐	☐ on ____ (DATE)
(f) Training program (Instruction 6–f)	☐	☐	☐ on ____ (DATE)
(g) Internal inspection system or other management control (Instruction 6–g)	☐	☐	☐ on ____ (DATE)
(h) Overall organizational structure (Instruction 6–h)	☐	☐	☐ on ____ (DATE)
(i) Leak testing procedures (Instruction 6–i)	☐	☐	☐ on ____ (DATE)

CERTIFICATE (This item must be completed by applicant)

7. THE APPLICANT AND ANY OFFICIAL EXECUTING THIS CERTIFICATE ON BEHALF OF THE APPLICANT NAMED IN ITEM 1, CERTIFY THAT THIS APPLICATION IS PREPARED IN CONFORMITY WITH TITLE 10, CODE OF FEDERAL REGULATIONS, PART 30, AND THAT ALL INFORMATION CONTAINED HEREIN, INCLUDING ANY SUPPLEMENTS ATTACHED HERETO, IS TRUE AND CORRECT TO THE BEST OF OUR KNOWLEDGE AND BELIEF

____
Applicant Named in Item 1

By: ____________________

DATE ____________________

____
Title of Certifying Official

WARNING.—18 U.S.C., Section 1001, Act of June 25, 1948; 62 Stat. 749; makes it a criminal offense to make a willfully false statement or representation to any department or agency of the United States as to any matter within its jurisdiction.

FIGURE 13.1.—Application for Byproduct Material License-Use of Sealed Sources in Radiography.

FORM AEC-313R (9-62)

LEGAL STRUCTURE OF APPLICANT

If applicant is a corporation, complete Items 8 through 11; if applicant is a partnership, complete Items 12 through 14; if applicant is an unincorporated association or a legal entity other than a partnership or corporation, complete Items 15 and 16. Attach separate sheets where space provided proves inadequate.

CORPORATION

8. STOCK OF APPLICANT CORPORATION

NO. OF SHARES AUTHORIZED	NO. OF SHARES ISSUED	NO. OF SHARES SUBSCRIBED	TOTAL NUMBER OF:	
			(a) Stockholders	(b) Subscribers

9. Is applicant corporation directly or indirectly controlled by another corporation or other legal entity? .... YES ☐ .... NO ☐
If answer is "YES" give name and address of other corporation or other legal entity and describe how such control exists and the extent thereof.

10. (a) Identify by name and address any individual, corporation, or other legal entity (1) owning 10 percent or more of the stock of applicant corporation issued and outstanding or (2) subscribing to 10 percent or more of the authorized but unissued stock of the corporation.
(b) Identify by name and address all officers and directors of the corporation.

11. Identify the State, District, Territory, or possession under the laws of which the applicant is incorporated.

PARTNERSHIP

12. Name and address of each individual or legal entity owning a partnership interest in the applicant.

13. State the percent of ownership of the applicant partnership held by each of the individuals or legal entities listed in Item 12.

14. Identify the State, District, Territory, or possession under the laws of which the applicant partnership is organized.

OTHER

15. Describe the nature of the applicant and identify the State, District, Territory, or possession under the laws of which it is organized.

16. State the total number of members or persons holding an ownership in the applicant, identify each by name and address, and indicate the ownership interest thereof.

FIG. 13.1.—Application for Byproduct Material License-Use of Sealed Sources in Radiography (reverse).

worker and the general public. They are also flexible enough to allow for industrial operations.

The standards for personnel protection are quite specific. Each of the rules is precise in outlining the quantities of radiation which can be tolerated and certain precautionary measures to be taken. Since these standards have been included in the industrial radiography licensing guide, only selected sections will be reviewed here.

13–5.1 *Definitions.* Since federal regulations are legal documents, care must be taken so that technical words will not be misinterpreted. Such terms as "byproduct material," "calendar quarter," "individual," "occupational dose," "person," "radiation," "radioactive material," "restricted area," "unrestricted area," "dose," "radiographer," "radiographer's assistant," "radiographic exposure device," "radiography," "sealed source," and "storage containers" have specified definitions for regulatory purposes. Although these terms are defined in various places in this text, the radiographer should familiarize himself with the precise definitions which appear in the glossary.

13–5.2 *Exposure of Individuals to Radiation in Restricted Areas.* In radiography operations it is impractical or impossible to prevent some exposure of individuals to radiation. For this reason radiography must always be performed in restricted areas. Equipment designs and controlled procedures will permit the radiographer to work without receiving excessive radiation doses.

Limitations on individual dosage have been set according to Table 13.1. The dosage should always be kept to a minimum. A general guide to follow is that the maximum average dose of 100 mr/wk will not exceed the "tolerance dose."

TABLE 13.1.—Exposure Limits in Restricted Areas (In any calendar quarter).

(1) Whole body; head and trunk; active bloodforming organs; lens of eyes; or gonads	1¼ rem
(2) Hands and forearms; feet and ankles	18¾ rem
(3) Skin of whole body	7½ rem

On occasion, certain operations require that an individual worker be exposed to radiation doses in excess of the limits shown above. This fact has been recognized and a procedure worked out which allows exposures up to 3 rems per calendar quarter provided the radiographer's accumulated dose does not exceed 5(N–18) (refer to paragraph 6–8.3). Before permitting an individual to receive such exposure, each licensee must record on suitable forms each period of time the individual has been occupationally exposed since his 18th birthday and have the individual sign the form prepared. (See Figures 13.2 and 13.3.) When for some reason the individual has no record of his occupational exposure, the licensee must use the arbitrary rates prior to January 1, 1961, of 3¾ rems or after January 1, 1961, 1¼ rems per calendar quarter for periods prior to this time. Note: if doses computed in this manner show exposure prior to January 1, 1961, to *exceed* 5(N–18) the excess amount need not be used in further computations of permissible rates of exposure.

13–5.3 *Permissible Levels of Radiation in Unrestricted Areas.* With proper controls, it is permissible to release radiation into unrestricted areas which does not exceed the following limits: 0.5 rem in one calendar year, 2 millirem in one hour, or 100 millirem in seven consecutive days.

It is believed that if an individual were continuously present to receive these accumulated dosages there could be no body harm.

13–5.4 *Exposure of Minors.* Radiation damage is more severe to growing organisms. For this reason no individual under 18 years of age is permitted to receive dosages exceeding 10 percent of the limits specified in Table 13.1.

There is a special regulation to protect persons under 18 years of age because of their greater susceptibility to radiation injury. Under normal conditions, such persons *will not* be involved in operations licensed for radiography. When they are, permissible exposure is one-tenth that for persons over 18 years of age.

13–5.5 *Symbols and Signs.* Regulatory requirements in many instances have created a public awareness of standardized safety colors, symbols, and signs. Radiation warning symbols and signs of a certain type are also required for specific situations. The design and other specifications of these symbols and signs are discussed in paragraph 13–6.4 and are illustrated in Figures 13.4, 13.5, 13.6, and 13.7.

FORM AEC-4
(9-60)

Form Approved.
Bureau of Budget No. 38-R119.
Expiration Date: June 30, 1961.

U.S. ATOMIC ENERGY COMMISSION

OCCUPATIONAL EXTERNAL RADIATION EXPOSURE HISTORY

See Instructions on the Back

IDENTIFICATION

1. NAME (PRINT—LAST, FIRST, AND MIDDLE)	2. SOCIAL SECURITY NO.
3. DATE OF BIRTH (MONTH, DAY, YEAR)	4. AGE IN FULL YEARS (N)

OCCUPATIONAL EXPOSURE—PREVIOUS HISTORY

5. PREVIOUS EMPLOYMENTS INVOLVING RADIATION EXPOSURE—LIST NAME AND ADDRESS OF EMPLOYER	6. DATES OF EMPLOYMENT (FROM—TO)	7. PERIODS OF EXPOSURE	PREVIOUS DOSE HISTORY	
			8. WHOLE BODY (REM)	9. INSERT ONE: RECORD OR CALCULATED

10. REMARKS

11. ACCUMULATED OCCUPATIONAL DOSE—TOTAL

13. CALCULATIONS—PERMISSIBLE DOSE

WHOLE BODY:

(A) PERMISSIBLE ACCUMULATED DOSE = 5(N-18) = __________ REM

(B) TOTAL EXPOSURE TO DATE (FROM ITEM 14) = __________ REM

(C) PERMISSIBLE DOSE = __________ REM

12. CERTIFICATION: I CERTIFY THAT THE EXPOSURE HISTORY LISTED IN COLUMNS 5, 6, AND 7 IS CORRECT AND COMPLETE TO THE BEST OF MY KNOWLEDGE AND BELIEF.

EMPLOYEE'S SIGNATURE DATE

14. NAME OF LICENSEE

FIGURE 13.2.—Occupational External Radiation Exposure History.

FORM AEC—5
(9-60)

Form approved.
Bureau of Budget No. 38-R120.
Expiration date: June 30, 1961.

U.S. ATOMIC ENERGY COMMISSION

Current Occupational External Radiation Exposure

See Instructions on the Back

IDENTIFICATION

1. NAME (PRINT—Last, first, and middle)	2. SOCIAL SECURITY NO.
3. DATE OF BIRTH (Month, day, year)	4. AGE IN FULL YEARS (N)

OCCUPATIONAL EXPOSURE

5. DOSE RECORDED FOR (Specify: Whole body; skin of of whole body; or hands and forearms, feet and ankles.)	6. PERMISSIBLE DOSE AT BEGINNING OF PERIOD COVERED BY THIS SHEET	7. METHOD OF MONITORING (e.g., Film Badge—FB; Pocket Chamber—PC; Calculations—Calc.

8. PERIOD OF EXPOSURE (From—to)	DOSE FOR THE PERIOD (rem)				13. RUNNING TOTAL FOR CALENDAR QUARTER (rem)
	9. GAMMA	10. BETA	11. NEUTRON	12. TOTAL	

LIFETIME ACCUMULATED DOSE

14. PREVIOUS TOTAL rem	15. TOTAL DOSE RECORDED ON THIS SHEET rem	16. TOTAL ACCUMULATED DOSE rem	17. PERM. ACC. DOSE 5(N — 18) = rem	18. PERMISSIBLE DOSE rem

19. NAME OF LICENSEE

FIGURE 13.3.—Current Occupational External Radiation Exposure.

13–5.6 *Limits on Levels of Radiation for Radiographic Exposure Devices and Storage Containers.* Certain regulations are designed to protect workers from radiation emanating from radiographic exposure devices. The standards which must be met for sealed sources in the shielded, i.e., "off" position for the separate classes are as follows:

Radiographic exposure devices measuring less than four (4) inches from the sealed source storage position to any exterior surface of the device shall have no radiation level in excess of 50 milliroentgens per hour at six (6) inches from any exterior surface of the device. Radiographic exposure devices measuring a minimum of four (4) inches from the sealed source storage position to any exterior surface of the device, and all storage containers for sealed sources or for radiographic exposure devices, shall have no radiation level in excess of 200 milliroentgens per hour at any exterior surface, and ten (10) milliroentgens per hour at one meter from any exterior surface.

13–5.7 *Radiation Survey Instruments for Radiographic Operations.* It is also required that calibrated and operable survey meters be used to survey radiation fields at operation sites. The instruments used must have a range capable of reading as low as 2 mr/hr and as high as 1,000 mr/hr. (It is not mandatory that this entire range be measurable on a single instrument.)

13–5.8 *Tagging Sources.* Some sealed sources are not fastened to or contained in a radiographic exposure device. Such sources are required to have permanently attached a durable tag at least one inch square upon which is printed the radiation caution symbol and the instruction "Danger—Radioactive Material—Do Not Handle. Notify Civil Authorities if Found."

13–6 Precautionary Procedures and Records Required of Licensees

Certain rules and regulations are enforced with regards to safety which are strictly precautionary procedures. These may be briefly stated as follows:

13–6.1 *Surveys.* Radiation surveys are required in the interest of safety. It is desirable, before using sources, to make calculations of the dose rates into restricted and unrestricted areas. During exposures, surveys must be made and records kept of the location of sources and of field intensities where personnel are likely to be exposed. After each exposure is completed, and after sources are "stored," surveys must be made to determine if the source has been properly shielded. In effect, radiation hazards incident to radiographic operations must be surveyed and evaluated, and records of these findings must be kept on file for review.

13–6.2 *Storage of Licensed Material.* The radiographer must make sure that unauthorized personnel do not have access to stored material at any time.

13–6.3 *Personnel Monitoring.* Each radiography licensee must provide film badges and a dosimeter (or pocket chamber) for each radiographer and radiographer's assistant to wear while performing radiographic operations.

13–6.4 *Caution Signs, Labels, and Signals.* The necessity for clearly marking radioactive materials and exposure areas is obvious as a precautionary procedure. However, since concepts of adequate signs, labels, and signals vary, and because standardization has advantages, the established rules are outlined here.

Licensees must place radiation caution symbols, Figure 13.4, and signs in a conspicuous

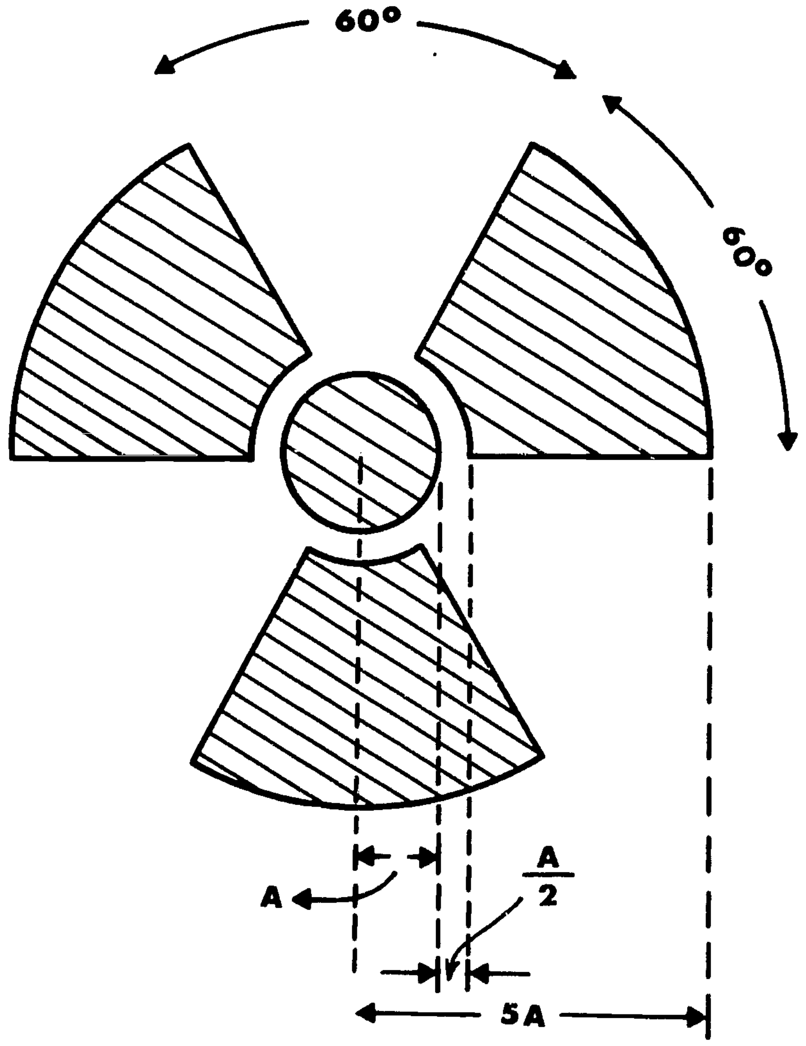


FIGURE 13.4.—Radiation Symbol.

place in all exposure areas, and on all containers in which radioactive materials are transported, stored, or used.

Each area, room, and container in which radiography sources are used or stored must be conspicuously posted with signs bearing the radiation symbol and the words CAUTION (or DANGER)—RADIOACTIVE MATERIAL (Figure 13.5).

FIGURE 13.5.—Radioactive Material Sign (symbol in magenta on a yellow background).

Radioactive material containers must have a tag or label stating the (1) kind of radioactive material therein, (2) quantity, and (3) date of measurement.

Radiation area means any area accessible to personnel in which radiation exists at such levels that a major portion of the whole body could receive in any one hour a dose exceeding 5 mrem, or in any 5 consecutive days a dose in excess of 100 mrem. Each radiation area must be conspicuously posted with signs bearing the radiation symbol and the words: CAUTION—(or DANGER) RADIATION AREA (Figure 13.6).

High radiation area means any area accessible to personnel in which radiation exists at such levels that a major portion of the whole

FIGURE 13.6.—Radiation Area Sign (symbol in magenta on a yellow background).

body could receive a dose exceeding 100 mrem in any one hour. Each high radiation area must be conspicuously posted with signs bearing the caution symbol and the words: CAUTION—(or DANGER) HIGH RADIATION AREA (Figure 13.7).

In addition to radiation warning signs, high radiation areas must be equipped with a control device which, upon entry by an individual, shall:

(1) reduce the radiation intensity to less than 100 mr/hr, or

(2) energize a conspicuous visible or audible alarm so the entering individual and the individual responsible for the high radiation area will be alerted that someone has entered the area.

In the event that a high radiation area is established for a period of less than 30 days, the control device is not required; however, it is most desirable that a responsible individual stand guard to restrain individuals from entering the radiation field.

FORM AEC-584
(12-61)

FIGURE 13.7.—High Radiation Area Sign (symbol in magenta on a yellow background).

13–6.5 *Instruction of Personnel and Notices to Employees.* Regulations in and of themselves are only partial answers to safeguarding the personnel of licensed operations. It is necessary that all personnel be familiar with the hazards and the safety precautions for them. Consequently, all licensees are required to:

(1) Inform every individual working in restricted areas of all radiation hazards present;
(2) Instruct all such individuals in the necessary safety practices and procedures for the types of hazards present;
(3) Instruct all personnel in the applicable provisions of regulations and licenses which apply to their protection;
(4) Advise employees of copies of radiation reports which they may request.

In addition each licensee must post in a conspicuous place, and at a place where employees pass on their way to and from work:

(1) Current copies of the AEC regulations relating to standards for protection against radiation
(2) A copy of the radiography license
(3) Operating procedures applying to the work under the license
(4) Figure 13.8 AEC Regional Office Locations.

If it is impractical to post the documents they may be kept available for employees' examination upon request.

13–6.6 *Waste Disposal.* The continued safety of the public demands safe disposal of radioactive wastes. However, since decayed radiography sources have such high activity the only practical means of disposal is to send the source to an authorized disposal company. Radiography sources are usually returned to the source vendor.

Licensees must not bury, incinerate, discard into the ocean or otherwise finally dispose of waste materials without license authorization.

13–6.7 *Security.* Security regulations require that a radiographer or radiographer's assistant shall maintain a direct surveillance of each radiographic operation to protect against unauthorized entry into a high radiation area. The only exceptions to this rule as previously brought out, occur when: (1) the high radiation area is equipped with a control device or alarm system or (2) the area is locked to protect against unauthorized or accidental entry.

13–6.8 *Records, Reports, and Notification.* Mention has already been made of some of the records which are required of licensees. All records and reports are studied periodically and must be carefully kept. It is also necessary to notify the proper authorities of thefts and mishaps and to provide employees and former employees with reports of their occupational exposure to radiation. The most important records are:

(1) Records of personnel monitoring must be kept which provide the information specified in Figure 13.3.
(2) Records of surveys must be prepared to show locations of radioactive sources, radiation field intensities, and protective measures to safeguard individuals.
(3) Records of quarterly inventory.
(4) Records of receipt and shipment of sources.
(5) Records of source utilization.
(6) Records of leak tests.

Reports and notifications which must be made include:

(1) Reports of personal dosage, if requested, shall be made to former employees.
(2) Reports, if requested, shall be made to employees of the annual dosage received.
(3) Reports of theft or loss of byproduct material shall be made to the nearest AEC Regional Office listed in Figure 13.8.

Immediate notification must be made to the manager of the appropriate AEC Regional Office of incidents involving:

(1) Byproduct source or special nuclear material which has caused or threatens to cause exposure of the whole body of any person to 25 rems or more of radiation, exposure of the skin of the whole body of any individual to 150 rems or more of radiation, or exposure of the feet, ankles, hands, or forearms of any individual to 375 rems of radiation.
(2) The release of radioactive material in concentrations which, if averaged over a period of 24 hours, would exceed 5,000 times the limits specified for such materials in Appendix B, Table II of Part 20 of CFR; or
(3) A loss of one working week or more of the operation of any facilities affected; or
(4) Damage to property in excess of $100,000.

For lesser incidents, the licensee is given 24 hours to notify the manager of the appropriate AEC Regional Office (see Figure 13.8) by telephone or telegraph. Incidents which fall in this class are:

(1) Exposure of the whole body of any individual to 5 rems or more of radiation; exposure of the skin of the whole body of any individual to 30 rems or more of radiation; or exposure of the feet, ankles, hands, or forearms to 75 rems or more of radiation; or
(2) The release of radioactive material in concentrations which, if averaged over a period of 24 hours, would exceed 500 times the limits specified for such materials in Appendix B, Table II of Part 20 of CFR; or
(3) A loss of one day or more of the operation of any facilities affected; or
(4) Damage to property in excess of $1,000.

13–7 Qualifications and Training of Radiography Personnel

Two types of radiography personnel, i.e., persons engaged in the actual handling and use of sealed sources of radiation and related equipment, are recognized by the AEC. A radiographer is defined as any individual who either performs radiography himself or who is in attendance at the site of use and personally supervises radiographic operations. The radiographer bears the direct responsibility to the licensee's management for compliance with regulations and license conditions. A radiographer's assistant is defined as a person who manipulates equipment and material related to radiography under the direct and personal supervision of a radiographer. A radiographer's assistant must be under surveillance at all times by a radiographer. The radiographer's assistant *cannot* exercise independent judgment in work related to radiography. The duties and responsibilities of a radiographer may not be delegated to a radiographer's assistant.

Because sealed sources used in radiography are hazardous if not properly used, persons who aspire to positions as radiographers or radiographer's assistants must meet certain minimum training and experience qualifications. In fact, it is mandatory that each applicant for a license to use byproduct material have an adequate program for training radiography personnel.

13–7.1 *Training Programs.* Training programs normally consist of four phases which may be elaborated as follows:

13–7.1a *The Initial Training Program.* The initial training program for radiographers must cover five major categories of subjects. The list of subjects is:

I. Fundamentals of radiation safety.
   A. Characteristics of gamma radiation.

Form AEC-3
(6-55)
10CFR20

UNITED STATES OF AMERICA ATOMIC ENERGY COMMISSION
Washington, D.C. 20545

NOTICE TO EMPLOYEES

STANDARDS FOR PROTECTION AGAINST RADIATION

In Part 20 of its Rules and Regulations, the Atomic Energy Commission has established standards for your protection against radiation hazards from radioactive material under license issued by the Atomic Energy Commission.

YOUR EMPLOYER'S RESPONSIBILITY

Your employer is required to—

1. Apply these *AEC regulations* and the *conditions of his AEC license* to all work under the license.
2. Post or otherwise make available to you a copy of the *AEC regulations, licenses,* and *operating procedures* which apply to work you are engaged in, and explain their provisions to you.

YOUR RESPONSIBILITY AS A WORKER

You should familiarize yourself with those provisions of the *AEC regulations,* and the *operating procedures* which apply to the work you are engaged in. You should observe their provisions for your own protection and protection of your co-workers.

WHAT IS COVERED BY THESE AEC REGULATIONS

1. Limits on exposure to radiation and radioactive material in restricted and unrestricted areas;
2. Measures to be taken after accidental exposure;
3. Personnel monitoring, surveys and equipment;
4. Caution signs, labels, and safety interlock equipment;
5. Exposure records and reports; and
6. Related matters.

REPORTS ON YOUR RADIATION EXPOSURE HISTORY

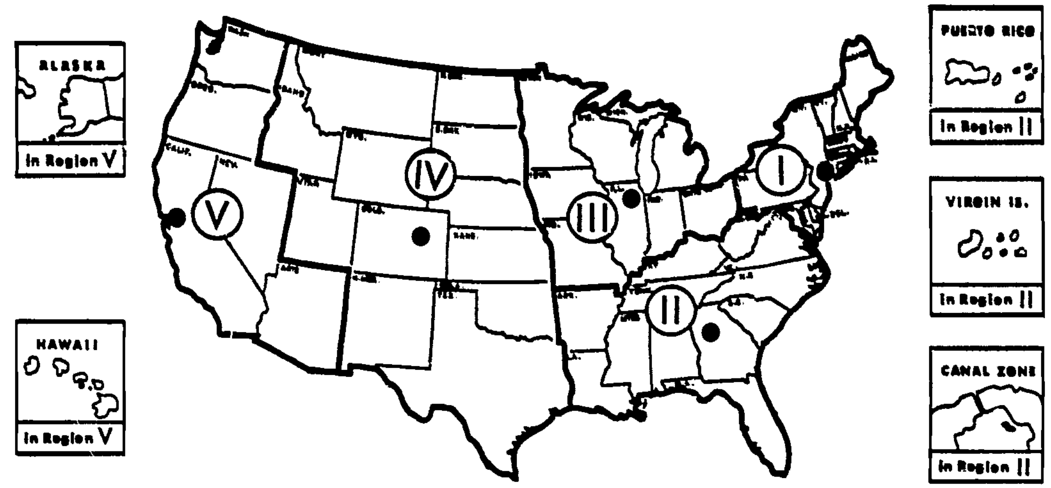
1. The AEC regulations require that your employer give you a written report if you receive an exposure in excess of any applicable limit as set forth in the regulations or in the license. The basic limits for exposure to employees are set forth in section 20.101, 20.103, and 20.104 of the Part 20 regulation. These sections specify limits on exposure to radiation and exposure to concentrations of radioactive material in air.
2. If you work where personnel monitoring is required pursuant to Section 20.202;
   (a) your employer must give you a written report of your radiation exposures upon the termination of your employment if you request it, and
   (b) your employer must advise you annually of your exposure to radiation if you request it.

INSPECTIONS

All activities under the license are subject to inspection by representatives of the U.S. Atomic Energy Commission.

INQUIRIES

Inquiries dealing with the matters outlined above can be sent to the United States Atomic Energy Commission Compliance Office having inspection responsibility over your plant, as shown on the map at the right.



POSTING REQUIREMENT

Copies of this notice must be posted in a sufficient number of places in every establishment where activities licensed by the AEC are conducted, to permit employees working in or frequenting any portion of a restricted area to observe a copy on the way to or from their place of employment.

UNITED STATES ATOMIC ENERGY COMMISSION
COMPLIANCE OFFICES

REGION	ADDRESS	TELEPHONE DAYTIME	TELEPHONE NIGHTS AND HOLIDAYS
I	Region I, Division of Compliance, USAEC 376 Hudson Street New York, New York 10014	212-989-1000	212-989-1000
II	Region II, Division of Compliance, USAEC 50 Seventh Street, Northeast Atlanta, Georgia 30323	404-526-5791	404-526-5791
III	Region III, Division of Compliance, USAEC Suite 410, Oakbrook Professional Building Oak Brook, Illinois 60523	312-654-1680	312-739-7711
IV	Region IV, Division of Compliance, USAEC 10395 West Colfax Avenue Denver, Colorado 80215	303-297-4811	303-237-5096
V	Region V, Division of Compliance, USAEC 2111 Bancroft Way Berkeley, California 94704	415-841-5630	415-841-5630

Attachment to Form AEC-3 (12/65). GPO 920-169

FIGURE 13.8.—AEC Regional Office Locations.

B. Units of radiation dose (mrem) and quantity of radioactivity (curie).
C. Hazards of excessive exposure of radiation.
D. Levels of radiation from licensed material.
E. Methods of controlling radiation dose:
   1. Working time
   2. Working distances
   3. Shielding

II. Radiation detection instrumentation to be used:
   A. Use of radiation survey instruments.
      1. Operation
      2. Calibration
      3. Limitations.
   B. Survey techniques.
   C. Use of personnel monitoring equipment
      1. Film badges
      2. Pocket dosimeters
      3. Pocket chambers.

III. Radiographic equipment to be used:
   A. Remote handling equipment.
   B. Radiographic exposure devices.
   C. Storage containers.

IV. The requirements of pertinent regulations.

V. The licensee's written operating and emergency procedures.

Each category of subjects must be separately identified by the applicant for a license, and the scope of planned training fully explained in the license application.

The training philosophy is that such programs should give the radiographer a practical approach to the understanding of the nature and potential hazard of radiation. To this end, training programs normally would include both formal instruction and on-the-job experience. Instruction must deal specifically with the radiation detection instrumentation, radiographic equipment, and operating and emergency procedures to be used in the applicant's radiography work. Prospective radiography personnel must also be instructed thoroughly in the operational procedures of the exposure devices they will use, including what to do in the event of equipment malfunction.

A review of the list of subjects required indicates that a given applicant for a license may not have employees with sufficient knowledge of radiation principles to provide the necessary instruction. If such is the case, the applicant may specify that initial training will be performed by qualified consultants, schools, or commercial companies which provide training courses for radiographers.

13–7.1b *Periodic Training.* It has been emphasized elsewhere that the field of nuclear science is rapidly changing. Insofar as radiography is concerned, changes in equipment and technology are constantly occurring which require revisions in operating and emergency procedures and the learning of new techniques. This is why the radiography personnel must receive updated instruction whenever changes occur in the radiography program. The licensee is made responsible for determining that both radiographers and radiographers' assistants have an understanding of all changes affecting their work and are competent to use new equipment, instruments, and procedures.

13–7.1c *On-the-job Training.* The necessary competency in the handling and use of exposure devices, sealed sources, etc., of trainees can only be demonstrated on the job. For this reason on-the-job training is considered a vital aspect of training radiography personnel. Licensees must provide sufficient time of this nature in their training programs to assure that trainees will have ample opportunity to learn how to handle all the equipment involved in their programs.

13–7.1d *Methods for Determining Qualifications of Personnel.* The last requirement, with regard to the training of radiographers, relates to the determination of competency. Procedures may range from comprehensive written and/or oral examination to personal observation. The applicant for a license may submit copies of typical examinations or describe the scope of testing, including sample questions. Evidence must also be included to indicate that a standard, unchanging type of examination ***will not*** be used over a long period of time. The requirements for radiography personnel may be summed up, as follows. No person can act as a radiographer or radiographer's assistant without successfully completing the prescribed training program. ***It is the responsibility of licensees*** to see that such training is received and that every radiographer is supplied with (1) copies of Parts 20 and 34 of the AEC regulations, (2) the operating and emergency procedures pertaining to the radiography operations, and (3) the AEC license under which this operation is done. Radiographers' assistants are only required to have copies of operating and emergency procedures, but may profit from copies of the pertinent regulations and licenses as well.

13–8 Organizational Structure of Radiography Programs

Regulations require that an applicant submit a description of the overall organizational structure of his radiography program. This is required because active control over the radiography program must be exercised by personnel in positions of authority. In the preparation of this application, it is necessary to show specifically how authority is established and responsibility delegated for operation of the program. This enables the identification of each individual in the chain of command by name and title and of the duties and responsibilities he will have in the radiography operations.

The *types* of duties which may be performed by management personnel vary as do the titles given such personnel. Some individual must be responsible for performing radiographic operations. Except in very small organizations, it is preferred that an additional individual be charged with management safety functions and be designated as a Radiation Safety Officer.

13–9 Other Requirements for Industrial Radiography Operations

After reading paragraph 13–3, the student will be aware that there are several other requirements which must be met before the license is issued for radiographic work. In addition to information already presented, knowledge of these requirements is necessary for the preparation of an application for a license.

13–9.1 *Internal Inspection System.* Applicants for a radiography license must establish and submit a satisfactory internal inspection system to assure that applicable regulations will be followed. This system must provide for active control over receipt, possession, use or transfer of radioactive materials procured under the license. It is especially designed to see that radiographers and radiographers' assistants follow the operating and emergency procedures specified in the license application.

There are, of course, many different types of radiography programs. The particular program will establish the frequency and scope of the internal inspection system. The adequacy of the system will be reviewed relative to the radiography programs proposed. Part of any such system will be continued review of records relating to receipt and disposal of licensed material and other records such as personnel monitoring, leak tests, quarterly inventories, utilization logs, and surveys. Such inspections are expected to be on both an announced and an unannounced basis.

13–9.2 *Operating and Emergency Procedures.* Paragraph 13–3 made reference to the fact that operating and emergency procedures had to be prepared for a specific license application and for the information of radiography personnel. The procedures which should be followed and the items which should be covered are briefly described here.

The first and most important fact to remember is that operating and emergency procedures should be prepared so as to fit the program which is proposed by the applicant.

Among the specific items which must be provided are:

(1) Step by step instructions on the handling of exposure devices and related equipment.
(2) Instructions on the operation, use, limitations, and malfunctions of the specific survey instruments which will be used.
(3) Description of methods for controlling access to radiographic areas, including ways for establishing and controlling restricted and unrestricted areas.
(4) Instructions on the detail of methods and occasions for locking and securing exposure devices and sealed sources.
(5) Instruction on personnel monitoring devices to be required.

(6) Instructions to personnel on procedures to follow in the event of accident or malfunction.
(7) Review of the records required.
(8) Description of the signs which will be used by radiographic personnel and instructions.
(9) Instructions for transporting radiographic sources.

13–9.3 *Leak Testing.* It is not frequent that a radioactive contamination problem develops in the use of a sealed radiography source. However, as a precautionary measure, it is required that each sealed source be tested for leakage at intervals not to exceed six months. The test made must be capable of detecting the presence of 0.005 microcurie of removable contamination on the sealed source. Records of leak testing must be kept to identify the (1) specific source, (2) date tested, and (3) results of the test. A sealed source received from others should be accompanied by a certificate showing an acceptable date and result of its last leak test. If such a certificate is missing, the source may not be used until another test has been completed. Details on leak testing are presented in paragraph 9–1.2b.

13–9.4 *Radiological Assistance.* There is always the possibility that an accident will occur which involves licensed material and threatens public health and safety. The Interagency Radiological Assistance Plan was developed by the Interagency Committee on Radiological Assistance as a means of providing rapid and effective assistance in the event of such an occurrence. Upon receiving a request for assistance, appropriate emergency assistance is provided, including radiation monitoring personnel and qualified medical personnel. Requests for assistance should be sent through the AEC–D.O.D. Joint Nuclear Coordinating Center. If radiological assistance is required, notify the nearest AEC Regional Office shown in Figure 13.8.

13–10 Transportation of Radioactive Materials

The comments included in this section are designed to be helpful in the interpretation and proper application of federal regulations relating to transportation of radioactive materials. Persons responsible for shipments of radioactive materials should familiarize themselves with the pertinent regulations of the Interstate Commerce Commission (ICC), the Civil Aeronautics Board (CAB), the U. S. Postal Service, or the U. S. Coast Guard.

There is no attempt here to discuss intrastate regulations, as these vary among the 50 States. For intrastate transportation, local authorities must be consulted.

13–10.1 *ICC Regulations.* All transportation of radioactive materials moving in interstate commerce by rail, water, or public highway (except for U. S. mail) is regulated by the ICC. Certain States extend ICC regulations to intrastate transportation as well.

The ICC regulations covering the Transportation of Explosives and Other Dangerous Articles include seven parts (Parts 71–77) of Title 49 of the Code of Federal Regulations. Individuals using their private automobiles for transporting personal property are not subject to these regulations so long as the property transported is not to be used in connection with a commercial enterprise.

ICC regulations have one major purpose—"to minimize the dangers to life and property incident to the transportation of explosives and other dangerous articles by common carriers engaged in interstate or foreign commerce." To this end, a philosophy has been adopted which represents a workable compromise between no shielding and gross overshielding. In the application of this philosophy, shielding is specified which provides "reasonable protection" to undeveloped films in transit and entirely adequate protection to humans.

13–10.1a *Materials Considered Dangerous.* Radioactive materials (poison D classification) considered dangerous are listed in the Federal Register. The purpose of this listing is to provide shippers with the (1) proper shipping name, (2) maximum quantity which can be shipped in an outside container, and (3) label which must be used for transportation purposes. Those materials of special interest to radiography work have been excerpted from the ICC list and are listed here.

TABLE 13.2.—Radioactive Materials Listed by ICC Commodity List.

Article	Classed as	Label required	Maximum quantity in one outside container by rail express
Cobalt-60	Poison D	Poison Radioactive Red	300 curies
Cesium-137	Poison D	Poison Radioactive materials Red	300 curies
Iridium-192	Poison D	Poison Radioactive materials Red	300 curies
Radioactive materials n.o.s. (not otherwise specified)	Poison D	Poison Radioactive materials Blue or red	

13–10.1b *Exemptions*. ICC regulations are intended to apply only to radioactive materials which represent a potential hazard during transportation. Arbitrary limits are therefore prescribed *below which* ICC regulations are not applied. *All packages whose radioactive content exceeds these limits must be packaged and labeled in accordance with ICC regulations.*

The tests for determining whether or not a package is exempt may be paraphrased as follows:

(1) Packages must be rugged enough to withstand conditions of ordinary transportation without allowing leakage of radioactive material.
(2) The total activity of the package contents must not exceed 0.1 millicurie of radium or polonium, or that amount of strontium 89, strontium 90, or barium 140 which disintegrates at a rate of more than 5 million atoms per second; or that amount of any other radioactive substance which disintegrates at a rate of more than 50 million atoms per second.
(3) The package must be so prepared that no significant alpha, beta, or neutron radiation is emitted from the exterior of the package and the gamma radiation at any part of its surface must be less than 10 milliroentgens for 24 hours.

The basis for the rather low limits for exemptions are explained in this manner. Not only must the possibility of accidental contamination under normal conditions be avoided but, in the event of a wreck, survivors and rescue workers ingesting or inhaling a substantial portion of the contents of the package must not be injured. Parcel wrappings must be free from external radioactive contamination which might be transferred to other parcels or persons. They must also be thick enough to absorb all alpha and beta rays emitted within the package so that adjacent film packages will not be damaged.

13–10.1c *Packing and Shielding*. All containers whose radioactive content or radiation emission exceeds permissible limits must be specially labeled and packaged. In addition, each container has to carry proper markings and descriptions and certification. Two criteria are accepted for specifying conditions for adequate packing and shielding:

(1) Under normal conditions the degree of fogging of undeveloped film must not exceed that produced by 11.5 milliroentgens of penetrating gamma rays of radium filtered by one-half inch of lead.
(2) There must be no significant radioactive surface contamination on any part of the container.

Radioactive materials used for radiography are sealed in metal capsules which prevent spread of contamination. This leaves only electromagnetic radiation to be controlled for shipping purposes. Some practical considerations for container and shielding designs are:

(1) Gamma radiation intensity must not exceed 200 mr/hr at any accessible container surface.
(2) Gamma radiation intensity must not exceed 10 mr/hr at one meter from any accessible container surface.
(3) All outside dimensions of the shipping container must be equal to or greater than 4 inches. (This dimension will prevent personnel from attempting to carry containers in their pockets. Also, lead shielding is most often used for radiography sources and the weight would be sufficient to eliminate unnecessary handling.)

(4) Containers for radiography sources must be equipped with a tamper seal. Even though it is not mandatory, many shipping containers are designed with locks and/or bolts to secure the covers.
(5) No more than 300 curies can be shipped in a container without special arrangements with the ICC.
(6) The container must be rugged enough to withstand shocks and loads encountered in ordinary transportation.

13–10.1d *Labeling.* Requirements for radioactive materials labels apply to all shipments which do not qualify for exemptions. These requirements are briefly as follows. For gamma ray (Group I) emitters, the shipper must attach to the outside of the package a Class D Poison, Group I or Group II label.

FIGURE 13.9.—Red Label, Class D Poison, Group I or II.

Such a label is commonly referred to as a "red label." The shipper must fill out the label so that it specifies: (1) the name of the principal radioactive element ("radium," "cobalt–60," etc.); (2) the activity of the contents of the package in disintegrations per second (dps) or in curies; (3) the number of "radiation units" from the package (for purposes of these regulations, 1 unit equals 1 mr/hr at 1 meter in all practical cases); and (4) the shipper's name.

A package of radioactive materials whose surface radiation is less than 10 mr/24 hr (0–0.4 mr/hr), but whose radioactive content is too great to qualify under the exemption clauses is required to have a so-called "blue label." This label is known technically as a Class D Poison label, Group III.

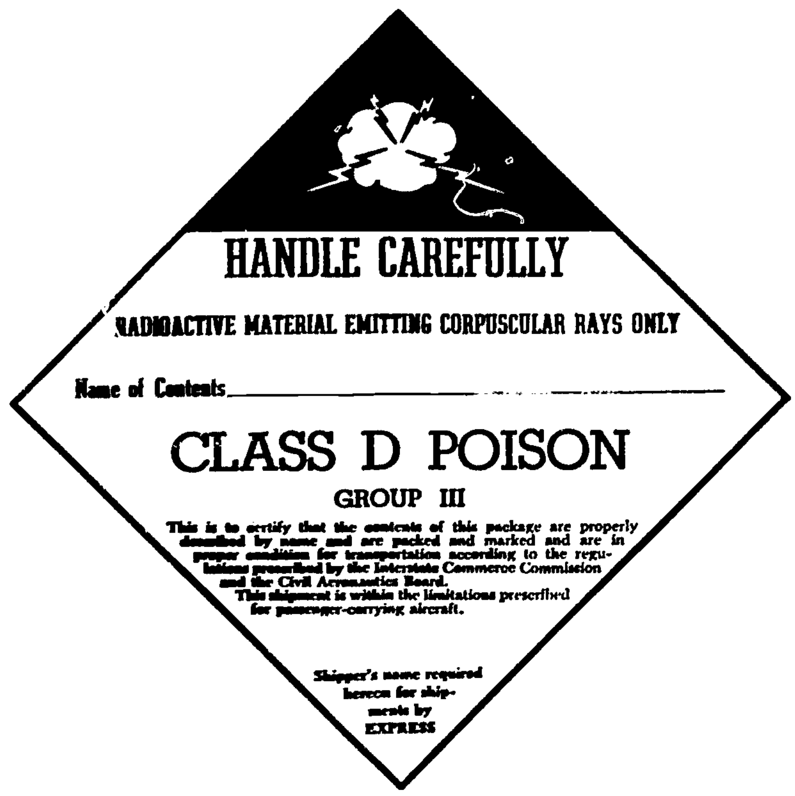


FIGURE 13.10.—Blue Label, Class D Poison, Group III.

Blue labels must show the name of the contents of the package, i.e., "carbon–14," "sulphur–35," etc., and the shipper's name.

When Group I or Group II materials are placed in a mixed package with Group III materials, both a red and a blue label must be used.

Blue label packages do not require segregation from either film or personnel. However, the regulations regarding fire, accident, breakage, proximity to explosives, and notification of shipper and Bureau of Explosives are the same as for red label packages.

Certain detailed instructions are included in the ICC regulations to guide shippers and carriers. These instructions forbid the use of radioactive-type labels on packages which are not subject to labels, and the use of labels which might be confused with standard caution labels, or which do not conform to size, color, and printing specifications.

13–10.1e *Placards and Markings.* The ICC prescribes that placards must be applied to railway cars, and motor vehicles transporting any quantity of radioactive materials. For railway cars the placard must be diamond shaped, measure $10\frac{3}{4}$ inches on each side and bear these words in red letters, DANGEROUS —RADIOACTIVE MATERIALS.

Motor vehicles and trailers carrying radioactive materials must be marked or placarded on each side and rear in letters not less than 3 inches high on a contrasting background as follows: DANGEROUS—RADIOACTIVE MATERIALS.

13–10.1f *Shipping Orders and Bills of Lading.* ICC regulations are to the point with regard to the descriptions which must be used on shipping papers. Shippers of radioactive materials by all usual modes of transportation must do two things: (1) use the name appearing in the ICC Commodity List (Table 13.2) in describing the articles on shipping orders, bills of lading, and other shipping papers; and (2) show thereon the color or kind of label applied to the package. It is permissible to add further descriptions consistent with the ICC Commodity List; however, abbreviations of any kind are expressly forbidden on shipping papers, because of the possibility of misinterpretation. It may be noted, as a reminder, that instructions included with the Commodity List indicate that all radioactive materials should be entered on shipping papers as "radioactive materials" and the proper group classification added.

13–10.1g *Certification.* The legal *responsibility of shippers* is usually assured through a certification procedure. Shippers offering radioactive materials for transportation by rail express must show their names on the package labels. Both red and blue labels contain a statement to this effect:

This is to certify that the contents of this package are properly described by name and are packed and marked and are in proper condition for transportation according to the regulations prescribed by the Interstate Commerce Commission.

13–10.1h *Empty Containers.* Three precautionary regulations apply specifically to empty containers. First, all containers and accessories which have been used for shipments of radioactive materials must be sufficiently free of contamination to be classified as exempt from packaging and labeling under the regulations as previously outlined. Second, ICC red and blue labels are prohibited on empty containers. These labels must be removed, obliterated or completely covered by an "empty" label. The latter is the third regulation which applies to empty containers. Such labels must be white, not less than 6 inches on each side and bear the word "empty" in letters not less than 1 inch high.

13–10.1i *Violations and Accidents.* Violations of ICC regulations and accidents must be reported to the ICC. Violations should be reported as quickly as possible, and in full detail, to the Bureau of Explosives, 50 Vesey Street, New York, N. Y.

In case of motor vehicle accidents involving the breakage of, or unusual delay of, shipments of radioactive materials, the package or material should be segregated as far as possible from human contact. Great care should be taken to prevent contact with, or inhalation of, radioactive material by humans. Both the shipper and the Bureau of Exposives must be notified immediately.

13–10.2 *Civil Air Regulations.* The Civil Aeronautics Board has regulatory authority over the transportation of radioactive materials by air. Its Civil Air Regulations (CAR) covering the Transportation of Explosives and Other Dangerous Articles constitutes Part 49 of Title 14 of the Code of Federal Regulations. These regulations were revised in 1949 to admit Class D poisons, i.e., radioactive substances.

Except for storage aboard aircraft, the CAR are essentially the same as ICC regulations. Some airlines have additional restrictions and the radiographer must determine these from the specific airline concerned with his service.

Certification requirements are imposed by the CAR as follows. No shipment may be made by air without a clear and plainly visible statement to the effect that all CAR regulations have been complied with. This statement must be signed by the shipper or his authorized agent, and attached to the package. Shippers must also certify that radioactive material on passenger-carrying aircraft fall within the limits prescribed for such aircraft. Passenger aircraft are not allowed to have dangerous cargo in their cabins.

13–10.3 *U. S. Postal Regulations.* Postal regulations relative to mailings of radioactive materials are included in the U. S. Postal Manual. The important fact for radiographers contemplating the mailing of radioactive materials is that only those parcels exempt from ICC specifications packaging and labeling are acceptable in the mails. *Red or blue label packages are nonmailable.*

Postal regulations state that any label required by Federal law or any Federal agencies must be pasted on the outside of radioactive packages. The nature of the contents must also be plainly shown on the outside of the package along with the full name and address of both the mailer and addressee, in ink, or rubber stamp, unless printed labels with this information are glued to the package.

A package containing radioactive materials must not emit from its exterior any significant alpha, beta, or neutron radiations and the gamma radiation at any surface of the package must be less than 10 milliroentgens for 24 hours.

For regulatory purposes, there is no distinction between the various classes of mail. Thus, packages which are "excluded from the mail" are ineligible for second class mail, air mail, and parcel post, as well as first class mail.

13–10.4 *U. S. Coast Guard Regulations.* For transportation by water, there is a divided responsibility. ICC regulations determine packaging and labeling requirements, but the acceptability, handling, and storage aboard ship are the responsibility of the U. S. Coast Guard.

The U. S. Coast Guard regulations governing the transportation of radioactive materials are included in Title 46, Part 146, of the Code of Federal Regulations. It may be noted that Coast Guard regulations, like CAR follow ICC regulations very closely; however, they apply to shippers making shipments of dangerous material by vessels and to the persons who own, control, or work aboard vessels.

In the event of accidents and violations of regulations notification should be submitted to the shipper and the District Commander of the U. S. Coast Guard.

13–11 Applying for a License to Use Radioisotopes for Radiography

When an individual or company desires to use radioisotopes for industrial radiography, it is required to apply for and receive a license before procuring the radioisotope or using the radioisotopes.

The U. S. Atomic Energy Commission is the national authority for this licensing activity. Several States have accepted the responsibility from AEC for radiography licensing. If the applicant does not know the proper agency or person to contact within his state, it is proper to write to:

The Division of Licensing and Regulations
U. S. Atomic Energy Commission
Washington, D. C. 20545

This Division will provide information on licensing requirements, procedures, and the proper responsible authorities.

The radiographer is again advised to obtain a copy of the "AEC Licensing Guide—INDUSTRIAL RADIOGRAPHY." This is available for 65 cents from the:

Superintendent of Documents
U. S. Government Printing Office
Washington, D. C. 20402

This bulletin is a guide on radiation safety considerations to be used in the preparation of license applications. Careful preparation of the license application along the format of this bulletin may save time in reviewing the license. The bulletin will certainly assist the careful reader to evaluate all facets of his radiation safety program.

Appendix A

Glossary of Useful Nuclear Terms in Industrial Radiography

ACTIVATION—the process by which neutrons bombard stable atoms to make them radioactive.

AGREEMENT STATE—A State which has accepted regulatory authority over byproduct materials from the USAEC.

ALPHA PARTICLE—A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons, hence it is identical to the nucleus of a helium atom.

ATOM—a particle of matter indivisible by chemical means. It is the fundamental building block of chemical elements.

ATOMIC NUMBER—denotes the number of protons in the nucleus, the number of positive charges in the nucleus, and the number of orbiting electrons.

ATOMIC WEIGHT (Atomic Mass Unit AMU)—the mass of an atom. The basis of a scale of atomic weights is the oxygen atom, and the commonest isotope of this element has arbitrarily been assigned an atomic weight of 16. Hence the unit of the scale is $1/16$ the weight of oxygen–16, or roughly the mass of the proton or neutron. The atomic weight of an element, therefore, is approximately equivalent to the total number of protons and neutrons in its neucleus.

AUTORADIOGRAPHY (*see also* radiography)—a picture produced upon a sensitive surface, e.g., a photographic film, by the rays from a radioactive substance contained within the specimen to be examined.

BACKGROUND RADIATION—the radiation of man's natural environment, consisting of that which comes from cosmic rays, the naturally radioactive elements of the earth, and from within man's body. The term may also mean radiation extraneous to an experiment.

BACKSCATTER—radiation scattered from the floor, walls, equipment, and other items in the area of a radiation source.

BANKING CONCEPT—an idea or model used to facilitate the explanation of radiation exposure permitted in a lifetime.

BARN—a very small unit of area used in measuring the cross sections of atoms, nuclei, electrons, and other particles. One barn is equal to 10^{-24} square centimeter. The term is a measure of the probability that a given nuclear reaction will occur.

BETA PARTICLE (Beta Ray)—an elementary particle emitted from a nucleus during radioactive decay. It has a single electrical charge and a mass equal to $1/1840$ that of a proton. Beta particles are easily stopped by a thin sheet of metal. A negatively charged beta particle is physically identical to the electron. If the beta particle is positively charged, it is called a positron. Beta radiation may cause skin burns, and beta emitters are harmful if inhaled or ingested.

BETATRON—an electron accelerator which uses magnetic induction to accelerate electrons in a circular path.

BODY BURDEN—the amount of radioactive material present in the body of man or animals.

BREMSSTRAHLUNG—electromagnetic radiation emitted by charged particles when they are slowed down by electric fields in their passage through matter. Literally "braking radiation" in German.

BONE SEEKER—a radioisotope that tends to lodge in the bones when it is introduced into the body.

BUILD-UP—an increase in radiation transmitted through material because of forward scatter.

BYPRODUCT MATERIAL—in atomic energy law, any radioactive material (except source or fissionable material) obtained in the process of producing or using source or fissionable material. Includes fission products and many other radioisotopes produced in nuclear reactors.

CASSETTE—a light tight carrier for films and screens.

CESIUM–137—a radioisotope of the element cesium.

CHAIN REACTION—a reaction that stimulates its own repetition. In a fission chain reaction, a fissionable nucleus absorbs a neutron and fissions, releasing more than one additional neutron. These in turn can be absorbed by other fissionable nuclei, releasing more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time interval equals or exceeds the number of neutrons absorbed.

COBALT-60—a radioisotope of the element cobalt.

COLD SHUT—a defect caused by streams of metal meeting in a casting but not properly flowing together.

COMPOUND—a chemical combination of elements.

COMPTON SCATTERING—a process in which a photon transfers a portion of its energy to an orbital electron in matter and a lower energy photon is scattered at an angle to the original photon path.

CONTAMINATION—the presence of unwanted radioactive matter, or the "soiling" of objects or materials with "radioactive dirt."

CONTRAST, RADIOGRAPHIC—differences in density from one area to another on a radiograph are termed radiographic contrast.

CONTRAST, SUBJECT—the ratio of radiation intensities passing through selected portions of a specimen.

CRACK—a discontinuity which has a relatively large cross section in one direction and a small or negligible cross section when viewed in a direction perpendicular to the first.

CROSS SECTION—a measure of the probability that a nuclear reaction will occur. Usually measured in barns, it is the apparent area presented by a target nucleus (or particle) to an oncoming particle.

CURIE—the basic unit used to describe the intensity of radioactivity in a sample of material. One curie equals 37 billion disintegrations per second, or approximately the radioactivity of 1 gram of radium.

DECAY—the spontaneous radioactive transformation of one nuclide into a different energy state of the same nuclide. Every decay process has a definite half-life (*see* also half-life).

DECONTAMINATION—the removal of radioactive contaminants from surfaces, as by cleaning and washing with chemicals.

DEFINITION—sharpness of the image on a radiograph.

DENSITY, PHOTOGRAPHIC (film density, optical density)—the darkening effect of a radiosensitive emulsion after exposure to radiation and chemical processing.

DETECTOR—a device which determines the presence of radiation.

DEUTERIUM—an isotope of hydrogen having mass equal to two AMU.

DEVELOPER—a chemical solution which reduces exposed silver halide crystals to metallic silver.

DISCONTINUITY—a term generally referring to any kind of flaw, defect, or lack of continuity in a material.

DOSE—the amount of ionizing radiation energy absorbed per unit mass of irradiated material at a specific location, such as a part of the human body. Measured in reps, rems, and rads.

DOSE RATE—the radiation dose delivered per unit time and measured, for instance, in rems per hour (*see* also dose).

DOSIMETER—a device that measures radiation dose, such as a film badge or ionization chamber.

ELECTROMAGNETIC RADIATION—radiation consisting of electric and magnetic waves that travel at the speed of light. Examples: light, radio waves, gamma rays, X-rays. All can be transmitted through a vacuum.

ELECTRON—an elementary particle with a unit negative electrical charge and a mass $1/1840$ that of the proton. Electrons surround the atom's positively charged nucleus and determine the atom's chemical properties.

ELECTRON VOLT—the amount of kinetic energy gained by an electron when it is accelerated through a voltage difference of 1 volt.

ELEMENT—one of the 104 known chemical substances that cannot be divided into simpler substances by chemical means. Examples: hydrogen, lead, uranium.

ELEMENTARY PARTICLE—originally a term applied to any particle that could not be further subdivided; now applied only to protons, electrons, neutrons, antiparticles, and strange particles, but not to alpha particles and deuterons.

EMISSIVITY—the energy emission rate usually expressed as r/c/hr @ 1 ft or mr/mc/hr @ 1 ft.

EMULSION—a gelatin and silver bromide crystal mixture coated onto a transparent film base.

ENCAPSULATION—the process of sealing radioactive materials to prevent contamination.

EXPOSURE, FILM—radiation intensity multiplied by time.

EXTERNAL DISCONTINUITIES—surface irregularities which cause density variations on a radiograph. These are observable with the naked eye.

FILM BADGE—a package of photographic film worn like a badge by workers in the nuclear industry to measure exposure to ionizing radiation. The absorbed dose can be calculated by the degree of film darkening caused by the irradiation.

FILM HOLDER—a light tight carrier for films and screens.

FISSION—the splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and frequently one or more neutrons. Fission can occur spontaneously, but usually it is caused by the absorption of gamma rays, neutrons, or other particles.

FISSION PRODUCTS—nuclei formed by the fission of heavy elements. They are of medium atomic weight; almost all are radioactive. Examples: strontium–90, cesium–137.

FISSIONABLE MATERIAL—any material readily fissioned by slow neutrons, for example, uranium–235 and plutonium–239.

FIXER—a chemical solution which dissolves unexposed silver halide crystals from developed film emulsions.

FLUX (neutron)—the intensity of neutron radiation. It is expressed as the number of neutrons passing through 1 square centimeter in 1 second.

FORWARD SCATTER—radiation scattered in approximately the same direction as the primary beam.

FUSION—the process by which two light nuclei combine to form a heavier nucleus.

GADOLINIUM–153—a radioisotope of the element gadolinium.

GAMMA RAYS—high-energy short-wavelength electromagnetic radiation emitted by a nucleus. Energies of gamma rays are usually between 0.010 and 10 Mev. X-rays also occur in this energy range, but are not of nuclear origin. Gamma radiation usually accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best attenuated by dense materials like lead and depleted uranium.

GEIGER COUNTER—a radiation detection and measuring instrument. It contains a gas-filled tube which discharges electrically when ionizing radiation passes through it. Discharges are counted to measure the radiation's intensity.

GENETIC EFFECTS OF RADIATION—effects that produce changes in those cells of organisms which give rise to egg or sperm cells and therefore affect offspring of the exposed individuals.

GOVERNMENT AGENCY—means any executive department, commission, independent establishment, corporation, wholly or partly owned by the United States of America which is an instrumentality of the United States, or any board, bureau, division, service, office, officer, authority, administration, or other establishment in the executive branch of the Government.

GRAININESS—the subjective impression of irregularity of the silver deposit on a photographic material.

HALF-LIFE—the time in which half the atoms in a radioactive substance disintegrate. Half-lifes vary from millionths of a second to billions of years.

HALF-LIFE, BIOLOGICAL—the time required for a biological system, such as a man or an animal, to eliminate, by natural processes, half the amount of a substance which has entered it.

HALF-VALUE LAYER—is that thickness of material required to absorb one half of the impinging radiation.

HIGH RADIATION AREA—means any area, accessible to personnel, in which there exists radiation originating in whole or in part within licensed material at such levels that a major portion of the body could receive in any one hour a dose in excess of 100 millirem.

HOLES—any void remaining in a specimen as a result of improper manufacturing processing. Often called gas holes, cavities, or air locks.

HOT CELL—a heavily shielded enclosure in which radioactive materials can be handled remotely through the use of manipulators and viewed through shielded windows so that there is no danger to personnel.

INCLUSION—any foreign matter contained in welds or castings.

INDIVIDUAL—means any human being.

INDUCED RADIOACTIVITY—radioactivity that is created by bombarding a substance with neutrons in a reactor or with charged particles produced by particle accelerators.

INVERSE SQUARE LAW—(at a distance from a point source) the intensity of radiation received varies as the inverse square of the distance of the source.

ION—an atom or molecule that has lost or gained one or more electrons. By such "ionization" it becomes electrically charged.

IONIZATION—the process of adding electrons to, or knocking electrons from, atoms or molecules, thereby creating ions. High temperatures, electrical discharges, and nuclear radiation can cause ionization.

IONIZATION CHAMBER—an instrument that detects and measures ionizing radiation by observing the electrical current created when radiation ionizes gas in the chamber, making it a conductor of electricity.

IONIZING RADIATION—any radiation that directly or indirectly displaces electrons from the orbital shell of atoms. Examples: alpha, beta, gamma radiation.

IRIDIUM-192—a radioisotope of the element iridium.

IRRADIATION—exposure to radiation, as in a nuclear reactor.

ISOTOPE—atoms with the same atomic number (same chemical element) but different atomic weights. An equivalent statement is that the nuclei have the same number of protons but different numbers of neutrons. Thus, ${}_6C^{12}$, ${}_6C^{13}$, and ${}_6C^{14}$ are isotopes of the element carbon, the subscripts denoting their common atomic numbers, the superscripts denoting the varying atomic weights.

LACK OF FUSION (incomplete penetration)—failure to properly fuse the base metal in a weld.

LEAK TEST—a test on sealed sources to assure that radioactive material is not being released.

LICENSED MATERIAL—source material, special nuclear material, or byproduct material received, possessed, used, or transferred under a general or special license issued by the Atomic Energy Commission.

LINEAR ACCELERATOR—a device for accelerating charged particles to very high velocities for producing X-rays.

MASS NUMBER—the sum of the neutrons and protons in a nucleus. The mass number of uranium-235 is 235. It is the nearest whole number to the atom's actual atomic weight.

MAXIMUM PERMISSIBLE DOSE (MPD)—that dose of ionizing radiation which competent authorities have established as the maximum that can be absorbed without undue risk to human health (*see* also radiation protection guide).

MEV—one million electron volts.

MICRO—a prefix that divides a basic unit by one million.

MILLI—a prefix that divides a basic unit by one thousand.

MINOR—any individual under 18 years of age.

MISRUN—a condition that occurs when the molten metal fails to fill the casting mold.

MOLECULE—a group of atoms held together by chemical forces. The atoms in the molecule may be identical: H_2, S_2, S_8; or different: H_2O, CO_2.

NEUTRON—an uncharged elementary particle with a mass nearly equal to that of the proton. The isolated neutron is unstable and decays with a half-life of about 13 minutes into an electron, proton, and neutrino. Neutrons sustain the fission chain reaction in a nuclear reactor.

NONDESTRUCTIVE TESTING—testing to detect internal and concealed defects in materials using techniques that do not damage or destroy the items being tested.

NUCLEAR REACTION—a reaction involving an atom's nucleus, such as fission, neutron capture, radioactive decay, or fusion, as distinct from a chemical reaction, which is limited to changes in the electron structure surrounding the nucleus.

NUCLEAR REACTOR—a device by means of which a fission chain reaction can be initiated, maintained, and controlled. Its essential component is a core with fissionable fuel. It usually has a moderator, a reflector, shielding, and control mechanisms.

NUCLEUS—the small, positively charged core of an atom. It is only about 1/10,000 the diameter of the atom but contains nearly all the mass. Except for ordinary hydrogen, all nuclei contain both protons and neutrons.

NUCLIDE—any species of atom that exists for a measurable length of time. A nuclide can be distinguished by its atomic weight, atomic number, and energy state. The term is used synonymously with isotope. A radio-nuclide is a radioactive nuclide.

OCCUPATIONAL DOSE—includes exposure of an individual to radiation (1) in a restricted area; or (2) in the course of employment in which the individual's duties involve exposure to radiation; provided that "occupational dose" shall not be deemed to include any exposure of an individual to radiation for the purpose of medical diagnosis or medical therapy of such individual.

PAIR PRODUCTION—the transformation of a high-energy ray into a pair of particles (an electron and a positron) during its passage through matter.

PARTICLE—a minute constituent of matter with a measurable mass, such as a neutron, proton, or meson.

PENETRAMETER—a small strip of the same material as a specimen and having a thickness which is in a definite ratio to the specimen thickness.

PERIODIC TABLE—a tabular arrangement of elements according to their properties.

PERSON—means (1) any individual, corporation, partnership, firm, association, trust, estate, public or private institution, group, Government agency other than the Commission, any State, any foreign government or nation or any political subdivision of any such government or nations, or other entity; and (2) any legal successor, representative, agent, or agency of the foregoing.

PERSONNEL MONITORING EQUIPMENT—means devices designed to be worn or carried by an individual for the purpose of measuring the dose received (e.g., film badges, pocket chambers, pocket dosimeters, film rings, etc.).

PHOTOELECTRIC EFFECT—a process by which electromagnetic radiation imparts energy to matter.

PHOTON—a discrete quantity of electromagnetic energy. Photons have momentum but no mass or electrical charge.

PITCHBLENDE—an ore which contains uranium.

POROSITY—a defect which consists of a collection of small holes in a material.

POROSITY CHARTS—standard charts for comparing porosity size and spacing.

POSITRON—an elementary particle with the mass of an electron but charged positively. It is the "antielectron." It is emitted in some radioactive disintegrations and is produced in pair production.

PROTON—an elementary particle with a single positive electrical charge and a mass approximately 1840 times that of the electron. The atomic number of an atom is equal to the number of protons in its nucleus.

R-METER—an ionization type instrument designed to measure radiation dose.

RAD—radiation absorbed dose. The basic unit of absorbed dose of ionizing radiation. One rad is equal to the absorption of 100 ergs of radiation energy per gram of matter.

RADIATION—the propagation of energy through matter or space in the form of waves. In atomic physics the term has been extended to include fast-moving particles (alpha and beta rays, free neutrons, etc.). Gamma rays and X-rays, of particular interest in atomic physics, are electromagnetic radiation in which energy is propagated in packets called photons.

RADIATION AREA—means any area, accessible to personnel, in which there exists radiation, originating in whole or in part within licensed material, at such levels that a major portion of the body could receive in any one hour a dose in excess of 5 millirem, or in any 5 consecutive days, a dose in excess of 100 millirems.

RADIATION PROTECTION GUIDE—the total amounts of ionizing radiation dose over certain periods of time which may safely be permitted to exposed industrial groups. These standards, established by the Federal Radiation Council, are equivalent to what was formerly called the "maximum permissible exposure."

RADIATION SAFETY OFFICER—an individual engaged in the practices of providing radiation protection. He is the representative appointed by the licensee for liaison with the Atomic Energy Commission.

RADIOACTIVE—atoms which are energetically unstable and decay to a stable condition by emitting radiation are said to be radioactive.

RADIOACTIVE MATERIAL—includes any such material whether or not subject to licensing control by the Commission.

RADIOACTIVITY CONCENTRATION GUIDE—the concentration of radioactivity in an environment which results in doses equal to those in the radiation protection guide. This Federal Radiation Council term replaces the former "maximum permissible concentration."

RADIOBIOLOGY—the study of the scientific principles, mechanisms, and effects of the interaction of ionizing radiation with living matter.

RADIOGRAPHER—means any individual who performs or who, in attendance at the site where the sealed source or sources are being used, personally supervises radiographic operations and who is responsible to the licensee for assuring compliance with the requirements of these regulations and the conditions of the license.

RADIOGRAPHER'S ASSISTANT—means any individual who, under the personal supervision of a radiographer, uses radiographic exposure devices, sealed sources or related handling tools, or survey instruments in radiography.

RADIOGRAPHIC CODE—a code for specifying minimum standards related to radiographic practices.

RADIOGRAPHIC EXPOSURE DEVICE—means any instrument containing a sealed source fastened or contained therein, in which the sealed source or shielding thereof may be moved, or otherwise changed, from a shielded to unshielded position for purposes of making a radiographic exposure. This may also refer to machines which produce ionizing radiation.

RADIOGRAPHY—means the examination of the structure of materials by nondestructive methods utilizing sealed sources of byproduct material and other sources of ionizing radiation.

RADIOISOTOPE—an unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. More than 1300 natural and artificial radioisotopes have been identified.

RADIOLOGY—that branch of medicine which uses ionizing radiation for diagnosis and therapy.

RADIUM—a radioactive element with the atomic number 88 and an atomic weight of 226. In nature, radium is found associated with uranium, which decays to radium by a series of alpha and beta emissions. Radium is used as a radiation source.

REDUCTION FACTOR—dose rate without a shield divided by the dose rate with a shield interposed between a source and a point at which radiation is measured.

REFERENCE RADIOGRAPHS—a group of radiographs containing images of discontinuities. These can be used as comparison "standards" for acceptability of materials.

RELATIVE BIOLOGICAL EFFECTIVENESS (RBE)—the relative effectiveness of a given kind of ionizing radiation in producing a biological response as compared with 250,000 electron volt gamma rays.

REM—roentgen equivalent man. A unit of absorbed radiation dose in biological matter. It is equal to the absorbed dose in rads multiplied by the relative biological effectiveness of the radiation.

REP—roentgen equivalent physical. An obsolete unit of radiation dosage, now superseded by the rad.

RESTRICTED AREA—means any area to which access is controlled by the licensee.

ROENTGEN—a unit of exposure dose of ionizing radiation. It is that amount of gamma or X-rays required to produce ions carrying 1 electrostatic unit of electrical charge in 1 cubic centimeter of dry air under standard conditions.

SAMARIUM–145—a radioisotope of the element samarium.

SCATTERING—a process that changes a particle's or photon's trajectory. Scattering is caused by collisions with atoms, nuclei, and other particles. If the scattered particle's energy is unchanged by the collision, elastic scattering prevails; if there is a change in energy, the process is called inelastic scattering.

SCREENS, RADIOGRAPHIC—metallic or fluorescent sheets used to intensify the radiation effect on films.

SEALED SOURCE—means any byproduct material that is encased in a capsule designed to prevent leakage or escape of the byproduct material.

SENSITIVITY, PERCENTAGE—a ratio of the smallest detectable thickness difference divided by the thickness of material being examined.

SENSITIVITY, RADIOGRAPHIC—a term usually referring to the ability of a radiographic procedure to detect discontinuities.

SHIELD—a layer or mass of material used to reduce the passage of ionizing radiation.

SHRINKAGE CAVITIES—cavities in castings caused by lack of sufficient molten metal as the casting cools.

SLAG INCLUSION—included slag in a weld or casting.

SOURCE—a radioactive material packaged so as to produce radiation for experimental or industrial use. In this manual the term "source" also refers to the "target" of an X-ray tube.

SOURCE MATERIAL—in atomic energy law, any material, except special nuclear material, which contains 0.05% or more of uranium, thorium, or any combination of the two.

SPECIAL NUCLEAR MATERIAL—in atomic energy law, includes plutonium, uranium-233, uranium containing more than the natural abundance of uranium-235, or any material artificially enriched by any of these substances.

SPEED, FILM—Film speed is inversely proportional to the exposure to attain a specified density.

SPILL—the accidental release of radioactive liquids.

SPOT EXAMINATION—local examination of welds or castings.

STABLE ISOTOPE—a nuclide that does not undergo radioactive decay.

STOP BATH—a mild acetic acid solution used to arrest film development.

STORAGE CONTAINER—means a device in which sealed sources are transported or stored.

SURFACE IRREGULARITIES—any change in material surface which renders the specimen unserviceable.

SURVEY—means an evaluation of the radiation hazards incident to the production, use, release, disposal, or presence of radioactive materials or other sources of radiation under a specific set of conditions. When appropriate, such evaluation includes a physical survey of the location of materials and equipment, and measurements of levels of radiation.

SURVEY METER—a portable instrument which measures dose-rate of exposure or radiation intensity.

THULIUM-170—a radioisotope of the element thulium.

TRACER—an element or compound that has been made radioactive so that it can be easily followed (traced) in biological and industrial processes. Radiation emitted by the radioisotope pinpoints its location.

TRITIUM—a radioactive isotope of hydrogen with two neutrons and one proton in the nucleus. It is heavier than deuterium (heavy hydrogen). Tritium is used in industrial thickness gages, as a label in tracer experiments, and in controlled fusion experiments.

TUNGSTEN INCLUSIONS—inclusions in welds resulting from particles or splinters of tungsten welding electrodes.

UNDERCUT, RADIOGRAPHY—an effect from scattered radiation that causes fuzzy edges of images on radiographs.

UNDERCUT, WELDING—a surface defect caused by melting the upper edge of a beveled weld face.

UNRESTRICTED AREA—means any area into which entry is not controlled by the licensee, and any area used for residential quarters.

UNSHARPNESS, GEOMETRICAL—the fuzziness or lack of definition in a radiographic image resulting from the source, size, object to film distance, and the source to object distance.

VAN DE GRAAFF GENERATOR—an electrostatic machine in which electrically charged particles are separated mechanically by a moving belt to build up a high potential on an insulated terminal. The particles are then accelerated along a discharge path through a vacuum tube by the potential difference between the insulated terminal and the opposite end of the machine.

WASTE, RADIOACTIVE—equipment and materials (from nuclear operations) which are radioactive and for which there is no further use.

X-RAY—penetrating electromagnetic radiation emitted when the inner orbital electrons of an atom are excited and release energy. Thus the radiation is not nuclear in origin and is generated in practice by bombarding a metallic target with high-speed electrons (*see* paragraphs 2 and 3 on page 11).

Appendix B

80–Hour Schedule for Radiography Training Program

1–Hour Session Number	1st Day	2nd Day	3rd Day	4th Day	5th Day	6th Day	7th Day	8th Day	9th Day	10th Day
1	General Instructions	Review SGL–1,2, 3,4	Review SGL– 5,6	IGL–9	Review SGL–7,8, 9,10	Mid-Term Exam	Review SGL–11	½ of SGL–13	Review SGL–13	LE–15
2	IG–Intro.	LE–1	LE–2	LE–3	LE–7	Mid-Term Exam	LE–10	LE–12	LE–14	LE–16
3	IGL–1	LE–1	LE–2	LE–3	LE–8	IGL–11	LE–10	LE–12	LE–14	LE–16
4	IGL–2	IGL–5	LE–4	IGL–10	LE–8	IGL–11	LE–10	LE–12	LE–14	LE–16
5	IGL–3	IGL–5	LE–4	LE–5	LE–8	LE–9	½ of IGL–13	IGL–12	Review SGL–12	Final Exam
6	IGL–4	IGL–6	LE–4	LE–5	LE–6	LE–9	LE–11	IGL–12	LE–13	Final Exam
7	SGL–1 SGL–2	SGL–5 SGL–6	IGL–7 IGL–8	LE–5	LE–6	LE–9	LE–11	SGL–12	LE–13	Final Exam
8	SGL–3 SGL–4	SGL–5 SGL–6	SGL–7 SGL–8	SGL–9 SGL–10	LE–6	SGL–11	LE–11	SGL–13	LE–13	Final Exam

IGL = Instructor's Guide Lesson
LE = Laboratory Exercise
SGL = Student Guide Lesson

Appendix C

Table of Squares and Square Roots

No. and Square or Square Root	and No.
1	1
2	4
3	9
4	16
5	25
6	36
7	49
8	64
9	81
10	100
11	121
12	144
13	169
14	196
15	225
16	256
17	289
18	324
19	361
20	400
21	441
22	484
23	529
24	576
25	625
26	676
27	729
28	784
29	841
30	900
31	961
32	1024
33	1089
34	1156
35	1225
36	1296
37	1369
38	1444
39	1521
40	1600
41	1681
42	1764
43	1849
44	1936
45	2025
46	2116
47	2209
48	2304
49	2401
50	2500
51	2601
52	2704
53	2809
54	2916
55	3025
56	3136
57	3249
58	3364
59	3481
60	3600
61	3721
62	3844

No. and Square or Square Root	and No.
63	3969
64	4096
65	4225
66	4356
67	4489
68	4624
69	4761
70	4900
71	5041
72	5184
73	5329
74	5476
75	5625
76	5776
77	5929
78	6084
79	6241
80	6400
81	6561
82	6724
83	6889
84	7056
85	7225
86	7396
87	7569
88	7744
89	7921
90	8100
91	8281
92	8464
93	8649
94	8836
95	9025
96	9216
97	9409
98	9604
99	9801
100	10000
101	10201
102	10404
103	10609
104	10816
105	11025
106	11236
107	11449
108	11664
109	11881
110	12100
111	12321
112	12544
113	12769
114	12996
115	13225
116	13456
117	13689
118	13924
119	14161
120	14400
121	14641
122	14884
123	15129
124	15376

No. and Square or Square Root	and No.
125	15625
126	15876
127	16129
128	16384
129	16641
130	16900
131	17161
132	17424
133	17689
134	17956
135	18225
136	18496
137	18769
138	19044
139	19321
140	19600
141	19881
142	20164
143	20449
144	20736
145	21025
146	21316
147	21609
148	21904
149	22201
150	22500
151	22801
152	23104
153	23409
154	23716
155	24025
156	24336
157	24649
158	24964
159	25281
160	25600
161	25921
162	26244
163	26569
164	26896
165	27225
166	27556
167	27889
168	28224
169	28561
170	28900
171	29241
172	29584
173	29929
174	30276
175	30625
176	30976
177	31329
178	31684
179	32041
180	32400
181	32761
182	33124
183	33489
184	33856
185	34225

No. and Square or Square Root	and No.
186	34596
187	34969
188	35344
189	35721
190	36100
191	36481
192	36864
193	37249
194	37636
195	38025
196	38416
197	38809
198	39204
199	39601
200	40000
201	40401
202	40804
203	41209
204	41616
205	42025
206	42436
207	42849
208	43264
209	43681
210	44100
211	44521
212	44944
213	45369
214	45796
215	46225
216	46656
217	47089
218	47524
219	47961
220	48400
221	48841
222	49284
223	49729
224	50176
225	50625
226	51076
227	51529
228	51984
229	52441
230	52900
231	53361
232	53824
233	54289
234	54756
235	55225
236	55696
237	56169
238	56644
239	57121
240	57600
241	58081
242	58564
243	59049
244	59536
245	60025
246	60516
247	61009

No. and Square or Square Root	and No.
248	61504
249	62001
250	62500
251	63001
252	63504
253	64009
254	64516
255	65025
256	65536
257	66049
258	66564
259	67081
260	67600
261	68121
262	68644
263	69169
264	69696
265	70225
266	70756
267	71289
268	71824
269	72361
270	72900
271	[illegible]
272	[illegible]
273	74529
274	75076
275	75625
276	76176
277	76729
278	77284
279	77841
280	78400
281	78961
282	79524
283	80089
284	80656
285	81225
286	81796
287	82369
288	82944
289	83521
290	84100
291	84681
292	85264
293	85849
294	86436
295	87025
296	87616
297	88209
298	88804
299	89401
300	90000
301	90601
302	91204
303	91809
304	92416
305	93025
306	93636
307	94249
308	94864
309	95481
310	96100

No. and Square or Square Root	and No.
311	96721
312	97344
313	97969
314	98596
315	99225
316	99856
317	100489
318	101124
319	101761
320	102400
321	103041
322	103684
323	104329
324	104976
325	105625
326	106276
327	106929
328	107584
329	108241
330	108900
331	109561
332	110224
333	110889
334	111556
335	112225
336	112896
337	113569
338	114244
339	114921
340	115600
341	116281
342	116964
343	117649
344	118336
345	119025
346	119716
347	120409
348	121104
349	121801
350	122500
351	123201
352	123904
353	124609
354	125316
355	126025
356	126736
357	127449
358	128164
359	128881
360	129600
361	130321
362	131044
363	131769
364	132496
365	133225
366	133956
367	134689
368	135424
369	136161
370	136900
371	137641
372	138384

TABLE OF SQUARES AND SQUARE ROOTS (Continued)

No. and Square or Square Root	and No.	No. and Square or Square Root	and No.	No. and Square or Square Root	and No.	No. and Square or Square Root	and No.	No. and Square or Square Root	and No.	No. and Square or Square Root	and No.
373	139129	394	155236	415	172225	436	190096	458	209764	479	229441
374	139876	395	156025	416	173056	437	190969	459	210681	480	230400
375	140625	396	156816	417	173889	438	191844			481	231361
376	141376	397	157609	418	174724	439	192721	460	211600	482	232324
377	142129	398	158404	419	175561			461	212521	483	233289
378	142884	399	159201			440	193600	462	213444	484	234256
379	143641			420	176400	441	194481	463	214369	485	235225
		400	160000	421	177241	442	195364	464	215296	486	236196
380	144400	401	160801	422	178084	443	196249	465	216225	487	237169
381	145161	402	161604	423	178929	444	197136	466	217156	488	238144
382	145924	403	162409	424	179776	445	198025	467	218089	489	239121
383	146689	404	163216	425	180625	446	198916	468	219024	490	240100
384	147456	405	164025	426	181476	447	199809	469	219961	491	241081
385	148225	406	164836	427	182329	448	200704			492	242064
386	148996	407	165649	428	183184	449	201601	470	220900	493	243049
387	149769	408	166464	429	184041	450	202500	471	221841	494	244036
388	150544	409	167281			451	203401	472	222784	495	245025
389	151321			430	184900	452	204304	473	223729	496	246016
		410	168100	431	185761	453	205209	474	224676	497	247009
390	152100	411	168921	432	186624	454	206116	475	225625	498	248004
391	152881	412	169744	433	187489	455	207025	476	226576	499	249001
392	153664	413	170569	434	188356	456	207936	477	227529		
393	154449	414	171396	435	189225	457	208849	478	228484	500	250000

Appendix D

"Need to Know"

A successful and competent radiographer needs to know all of the basic subject material presented in this Manual *PLUS* additional published subject matter. He must also have long experience in the shop and field performing industrial radiographic operations with many different types of gamma ray and X-ray sources on multitudes of various specimens.

Since this Training Program has been outlined for presentation in 80 hours, it is not deemed possible to learn all of the subject matter in this Manual. For this reason a "priority" list follows which suggests the instructor and student place primary interest on learning these topics. The knowledge gained from studying these items will permit the beginning radiographer to safely make radiographs. Continued study and experience will lead to competence.

Topics That Must Be Learned

TOPIC NUMBER	TITLE
Par. 2–4	Properties of Radiation
Par. 3–7	Decay of Radioactivity
Par. 3–8	The Curie
Par. 3–9	Plotting Radioactive Decay
Par. 4–1	Ionization and Ions
Par. 4–4	The Roentgen
Par. 4–5	Radiation Attenuation
Par. 4–6	Absorption of Radiation (Know concept only. It is not mandatory to be able to solve exponential equations.)
Par. 4–7	Half-value Layers
Par. 4–8	Reduction Factors
Par. 4–9	Principles of Radiation Safety
Par. 5–1	Radiation Detection and Measurement
Par. 5–2	Radiation Measurement
Par. 5–3.2	The Pocket Dosimeter and Pocket Chamber
Par. 5–4	Survey Meters
Par. 5–5	Instrument Characteristics
Par. 5–6	Instrument Calibration
Par. 5–7	Source Calibration
Par. 6–1	Radiation Health in Perspective
Par. 6–3	Measurement Units of Radiation Doses
Par. 6–4	The Nature of the Radiation Health Problem
Par. 6–8	Personnel Monitoring
Par. 6–12	Contamination (Refer to Laboratory Exercise 15 for information on leak testing.)
Chapter 8	Introduction to Radiography
Chapter 9	Elements of Industrial Radiography
Chapter 10	Radiographic Film
Chapter 11	Radiography Techniques
Chapter 12	Interpretation of Radiographs
Chapter 13	Government Licensing, Health, and Transportation Regulations for Isotope Radiography

Darkroom Don'ts

DON'TS—RULES	WHY—REASONS	WHAT TO DO—ACTIONS
General	*General*	*General*
1. Don't use a darkroom without adequate lead protection.	Lead protects the film from fogging and the technicians from X-ray exposures.	Insist upon adequate lead protection, usually, 1.5 mm of lead.
2. Don't permit the darkroom to become too hot—about 75° F.	A hot room makes the regulation of solution and temperatures difficult.	Use electric fans and outside ventilation if possible.
3. Don't guess at processing times.	Most individuals can not estimate time accurately enough for darkroom requirements.	Always use darkroom timer or clock.
4. Don't store large quantities of films.	Films deteriorate with age.	Keep a small surplus; renew your supply frequently.
5. Don't keep boxes of films lying flat.	Static charges of electricity may collect from pressure.	Stand film boxes on end.
Cassettes and screens	*Cassettes and screens*	*Cassettes and screns*
6. Don't permit screens to become dirty.	Dirt reduces screen sensitivity, resulting in spotted films.	Wash screens monthly—use pure grain alcohol and lint-free cloth.
7. Don't load, unload, or leave cassettes near processing tanks.	Drops of liquid may be splashed on the screens, reducing their sensitivity.	Keep loading bench far away from solutions.
8. Don't leave cassettes open.	Exposes screens to damage by dirt, liquids, and other objects.	Keep cassettes closed when not in use.
9. Don't rub or scratch screen surfaces.	Decreases screen life by destroying protective coat.	Brush screen surface lightly—use soft materials, such as a camel's hair brush.
10. Don't touch screen surfaces with your fingers.	The oil in finger prints reduces screen sensitivity.	When exchanging screens, touch only the edges.
Dry films	*Dry films*	*Dry films*
11. Don't bend, crease, press, or buckle films.	Black, half-moon marks may occur.	Handle films carefully to keep surfaces flat and smooth.
12. Don't scratch films with finger nails or other hard objects.	Scratches appear as light or dark streaks on films.	Use finger tips and not nails when handling films.
13. Don't slide or shuffle dry films over flat surface.	Films may become scratched; static electricity may develop.	When films are moved, free them from all supporting surfaces.
14. Don't leave film boxes uncovered.	Films become fogged with irregular markings.	Keep film boxes closed and in a dark cabinet when not in use.
15. Don't pile films on top of one another before mounting on the hangers.	Static electricity may be developed.	When film is removed from the cassette, place it on a hanger immediately.
Chemicals and solutions	*Chemicals and solutions*	*Chemicals and solutions*
16. Don't use same paddle to stir developer and hypo.	Developer may become contaminated with hypo.	Have one paddle for developer; another for hypo.
17. Don't mix developer in vessels other than glass, stainless steel, enamel, or earthenware.	Other materials contaminate the solutions and destroy their action.	Use glass, stainless steel, enamel, or earthenware vessels for mixing solutions.
18. Don't use scouring powder to cleanse the tanks.	Scouring powder is difficult to remove. May "spot" films.	Use stiff brush and water to cleanse tanks.
19. Don't leave solutions uncovered when not in use.	They may become contaminated with dirt. There may be loss of water by evaporation.	Keep processing tanks covered with semi-tight lid when not in use.

Bibliography

Information on industrial radiography has been published in many professional and technical journals, a few texts and handbooks, and several "codes." Selected references have been footnoted in this manual. Most of the subject matter has been drawn from the materials listed below. Grateful acknowledgement is made to these publishers and authors for permission to quote from the titles listed.

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